Single Photon Counting with the Quantum Capacitance Detector

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Electron Beam Lithography by Richard E.Muller
Fresnel lens array by Daniel Wilson

Single photon detection of 1.5 THz radiation with the quantum capacitance detector, P. M. Echternach , B. J. Pepper, T. Reck and C. M. Bradford, Nature Astronomy, Volume: 2 Issue: 1 Pages: 90-97 Published: JAN 2018; published on line Nov 2017

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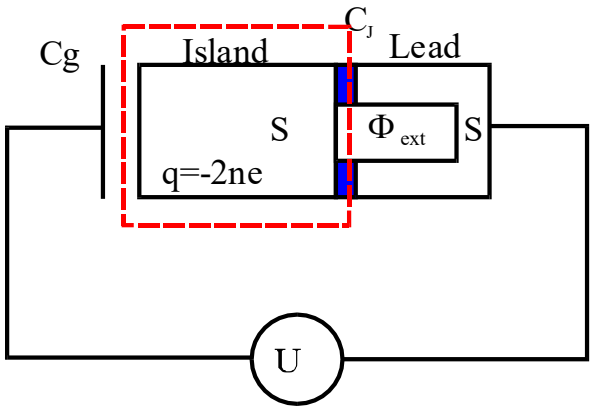
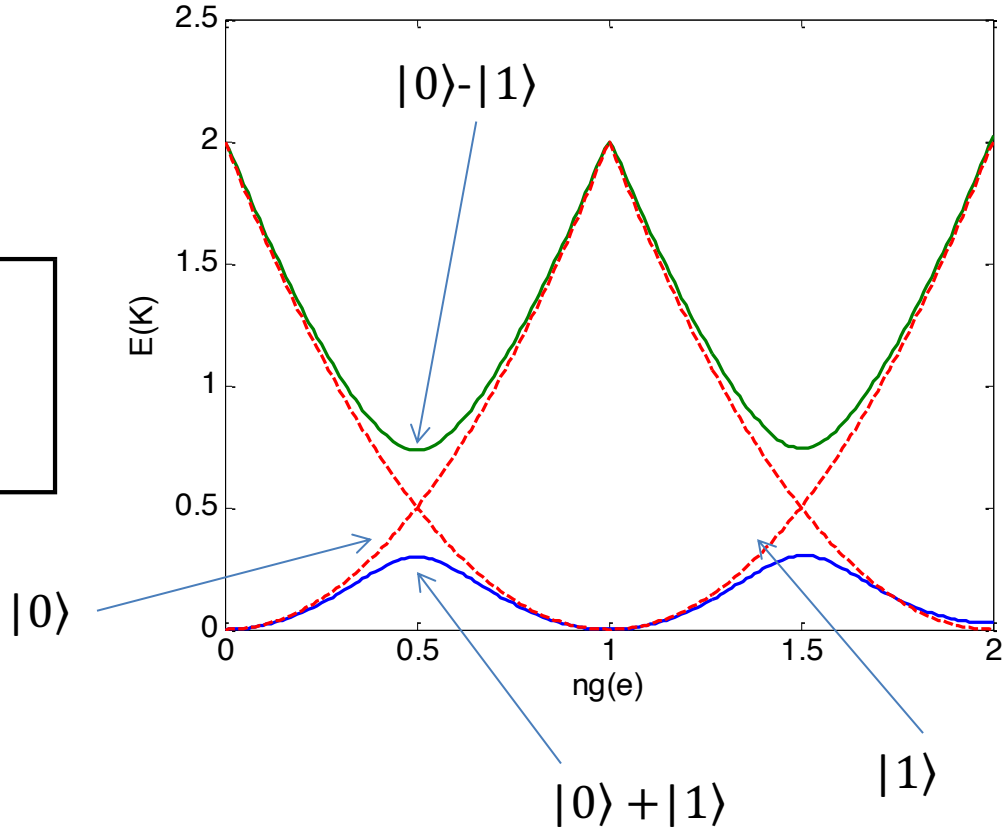
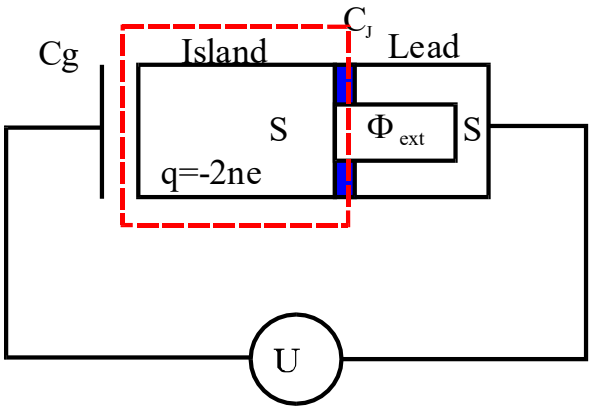
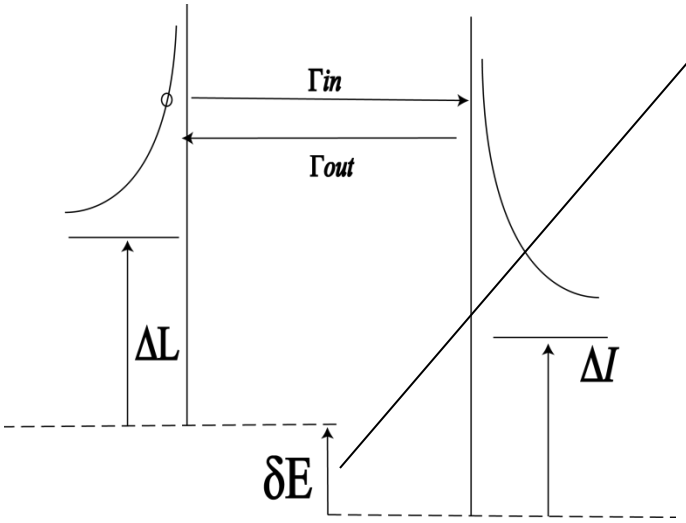
Single Cooper-pair Box (SCB) – developed as a Qubit

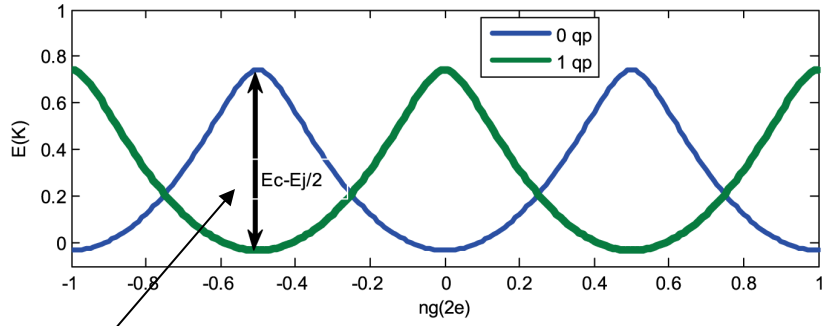


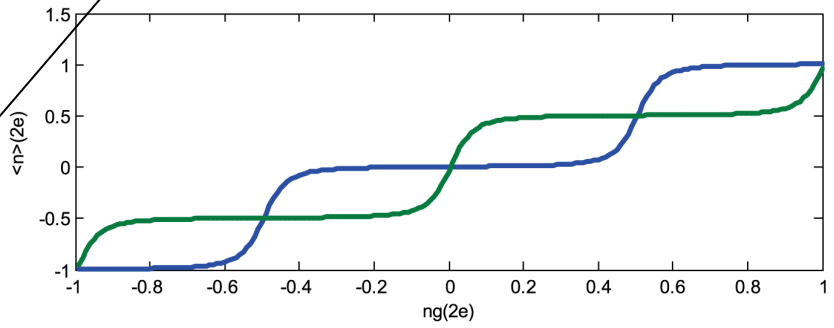


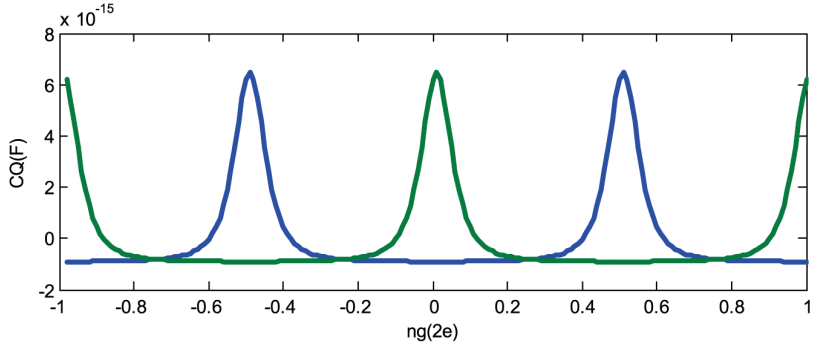
Single Cooper-pair Box (SCB)





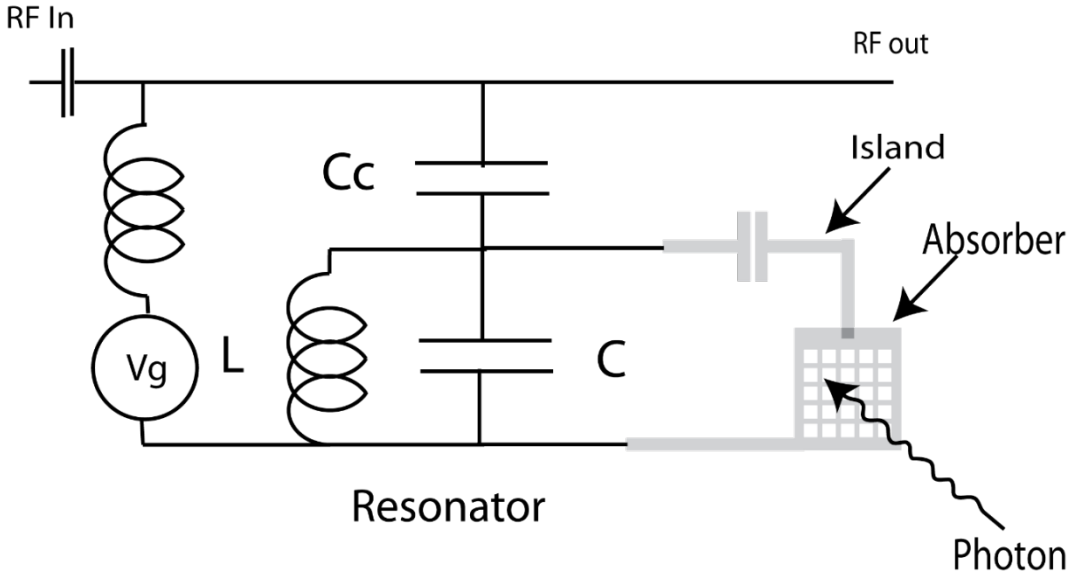


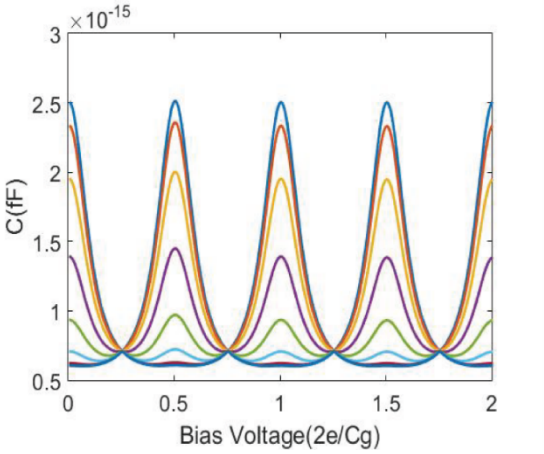


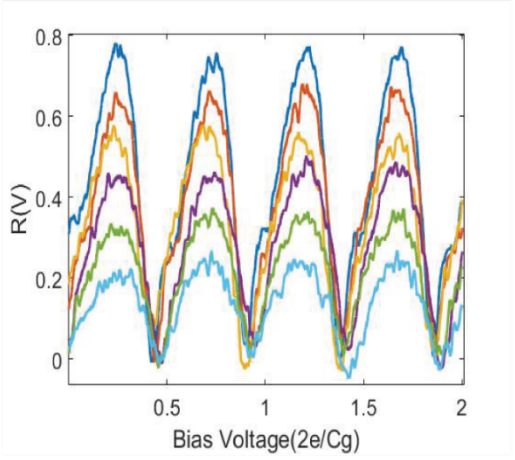


M. D. Shaw, J. Bueno, P. K. Day, C. M. Bradford, and P. M. Echternach, Phys. Rev. B **79**, 144511 2009.

Quantum Capacitance Detector

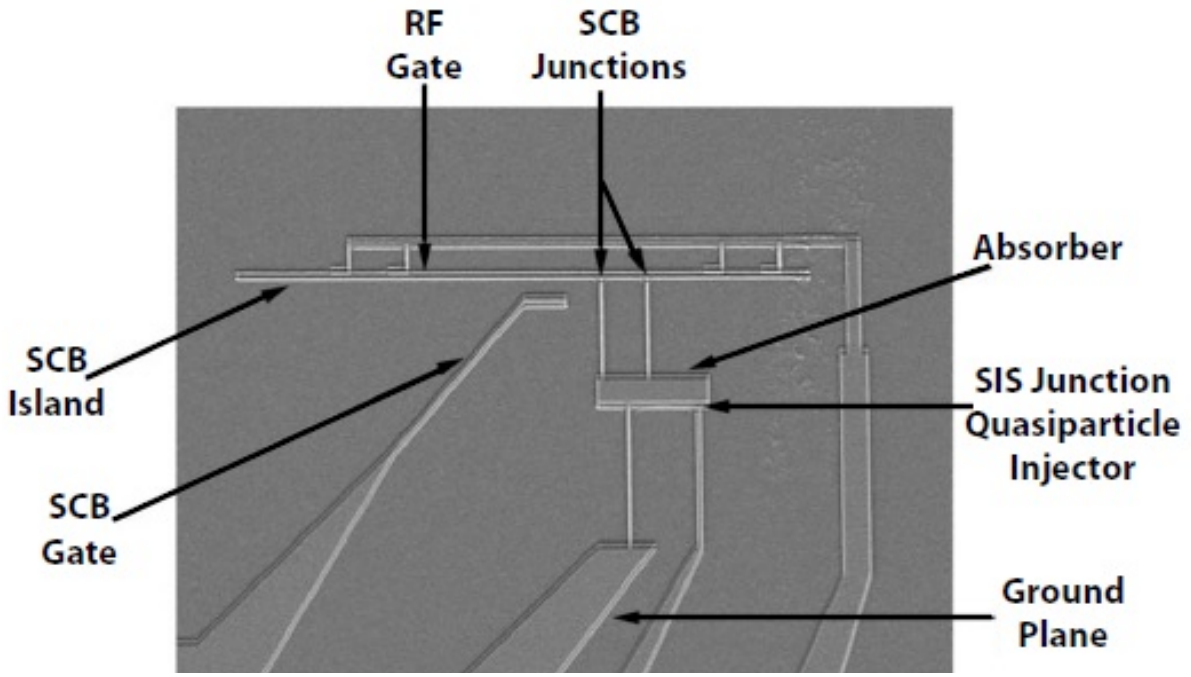


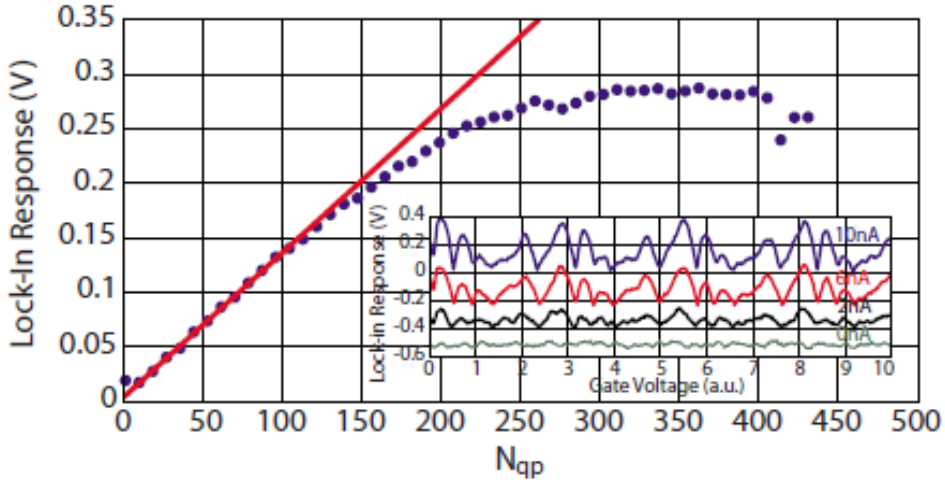




M. D. Shaw, J. Bueno, P. K. Day, C. M. Bradford, and P. M. Echternach, Phys. Rev. B **79**, 144511 2009.

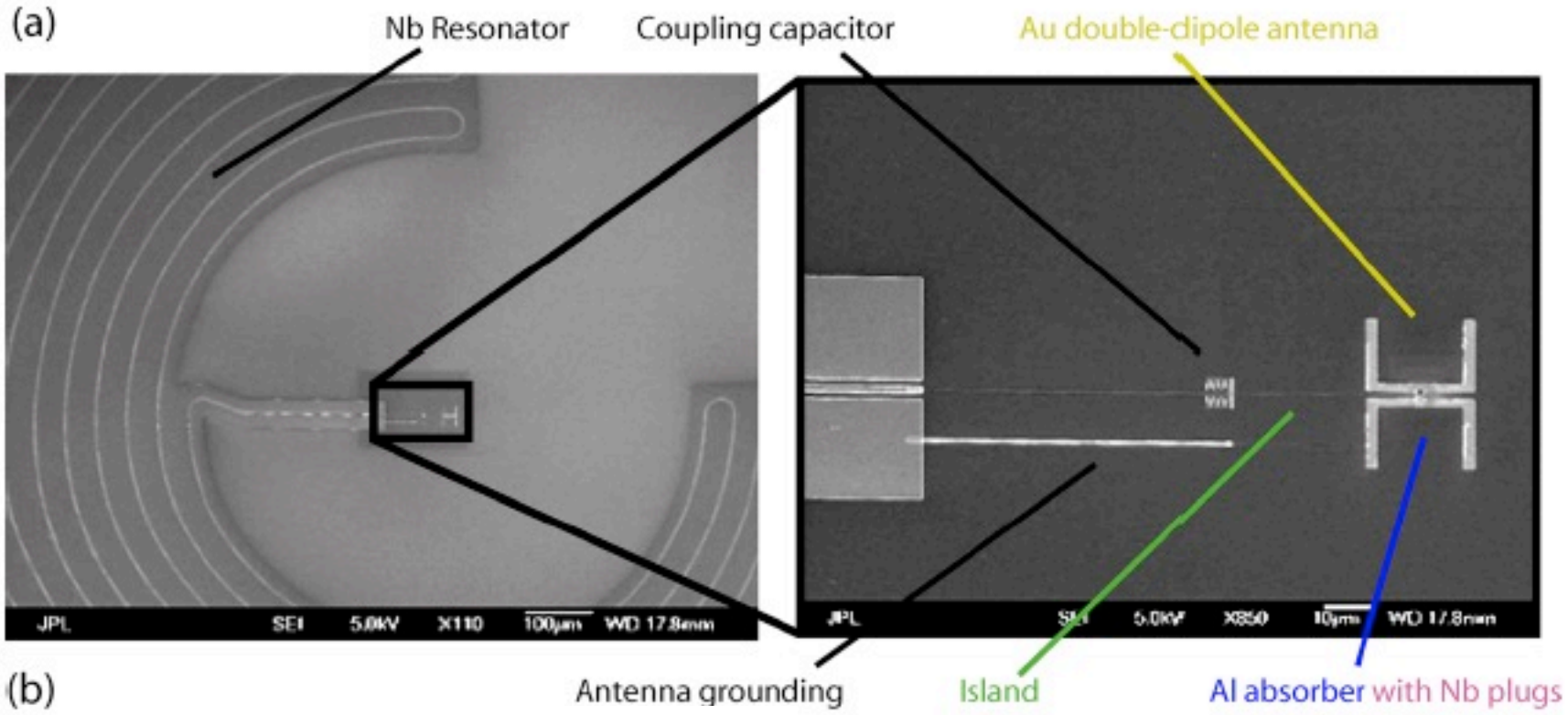
Proof of concept

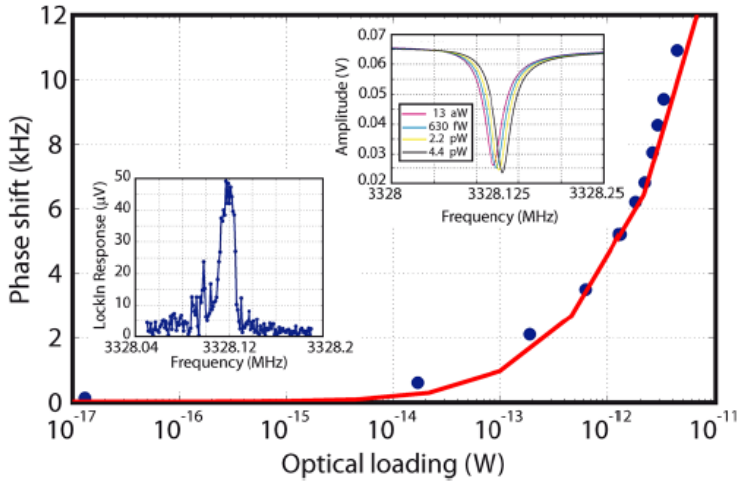




Bueno, J., Shaw, M.D., Day, P.K. & Echternach, P.M., Proof of Concept of the Quantum Capacitance Detector. *Appl. Phys. Lett.* **96,** 103503 (2010).

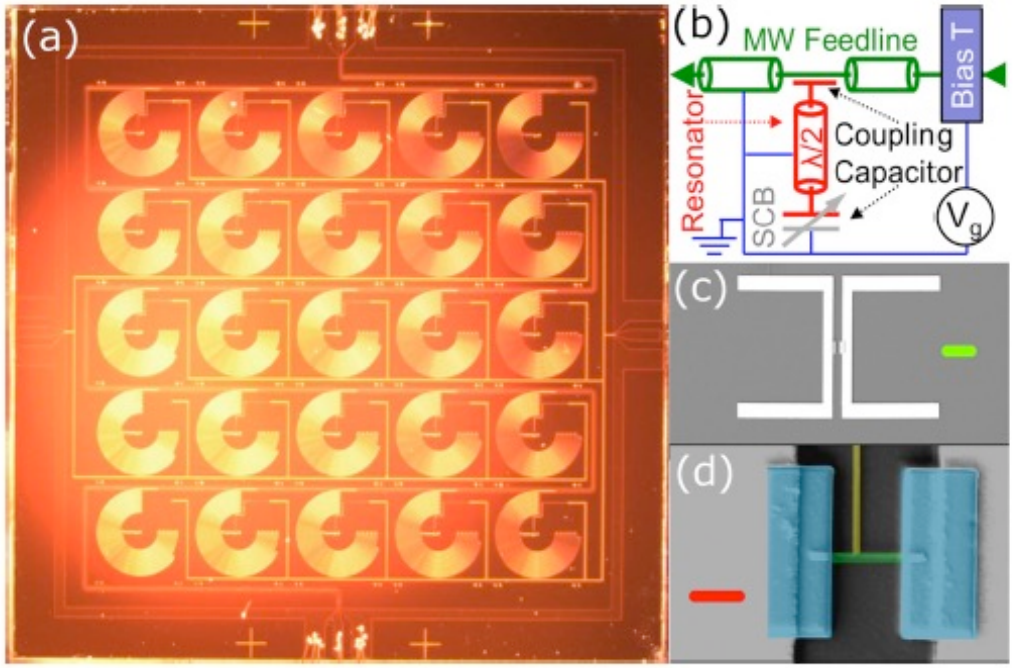
First prototype

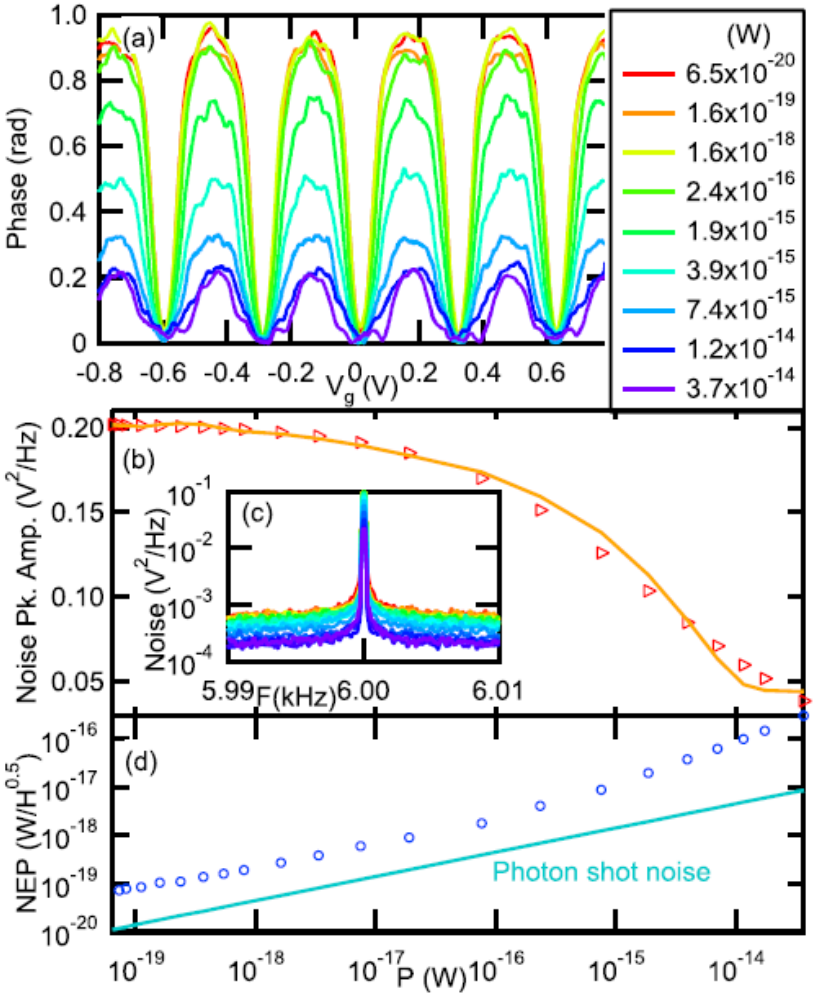




Bueno, J., Llombart, N., Day, P.K. & Echternach, P.M. Optical characterization of the quantum capacitance detector at 200 µm. *Appl. Phys. Lett.* **99,** 173503 (2011).

First array

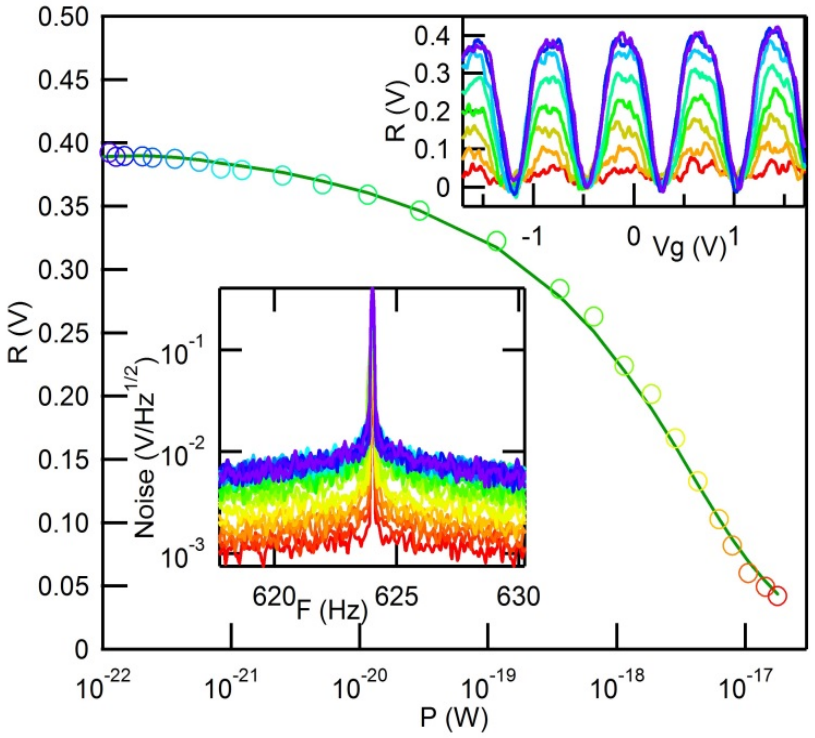




Stone, K.J., *et al.* Real time quasiparticle tunneling measurements on an illuminated quantum capacitance detector. *Appl. Phys. Lett.* **100**, 263509 (2012).

The Quantum Capacitance Detector

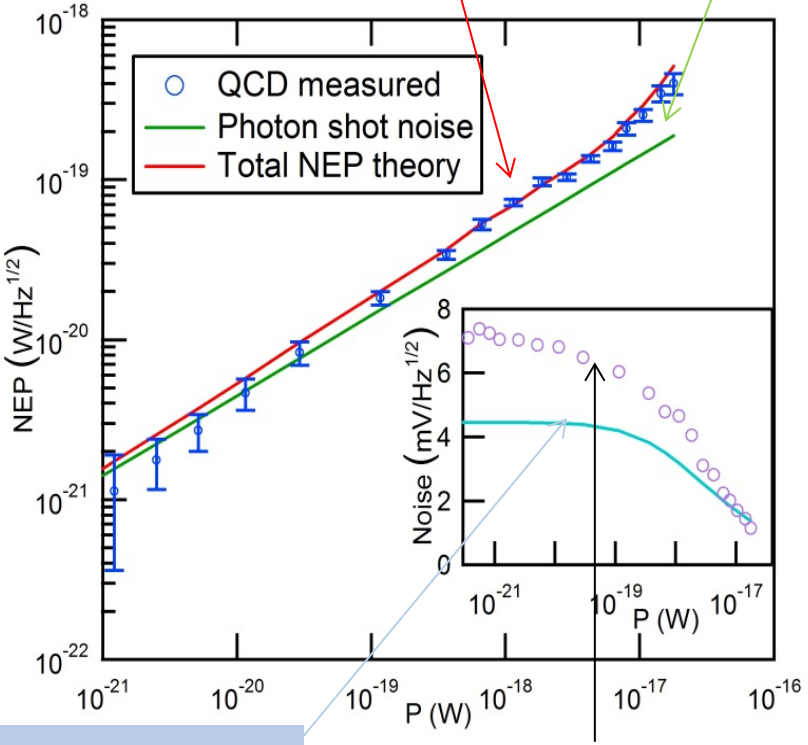
Response and noise as a function of optical signal



NEP as a function of optical signal
Photon shot noise limited!

$$NEP_{tot} = \sqrt{NEP_{ph}^2 + NEP_{sn}^2}$$

$$NEP_{ph} = \sqrt{2h\nu P_s}$$



Shot noise of electron tunneling

$$S_{sn}(f) = \sqrt{2A^2(\Gamma_{in}\Gamma_{out}/\Gamma_\Sigma)/(\Gamma_\Sigma^2 + (2\pi f)^2)}$$

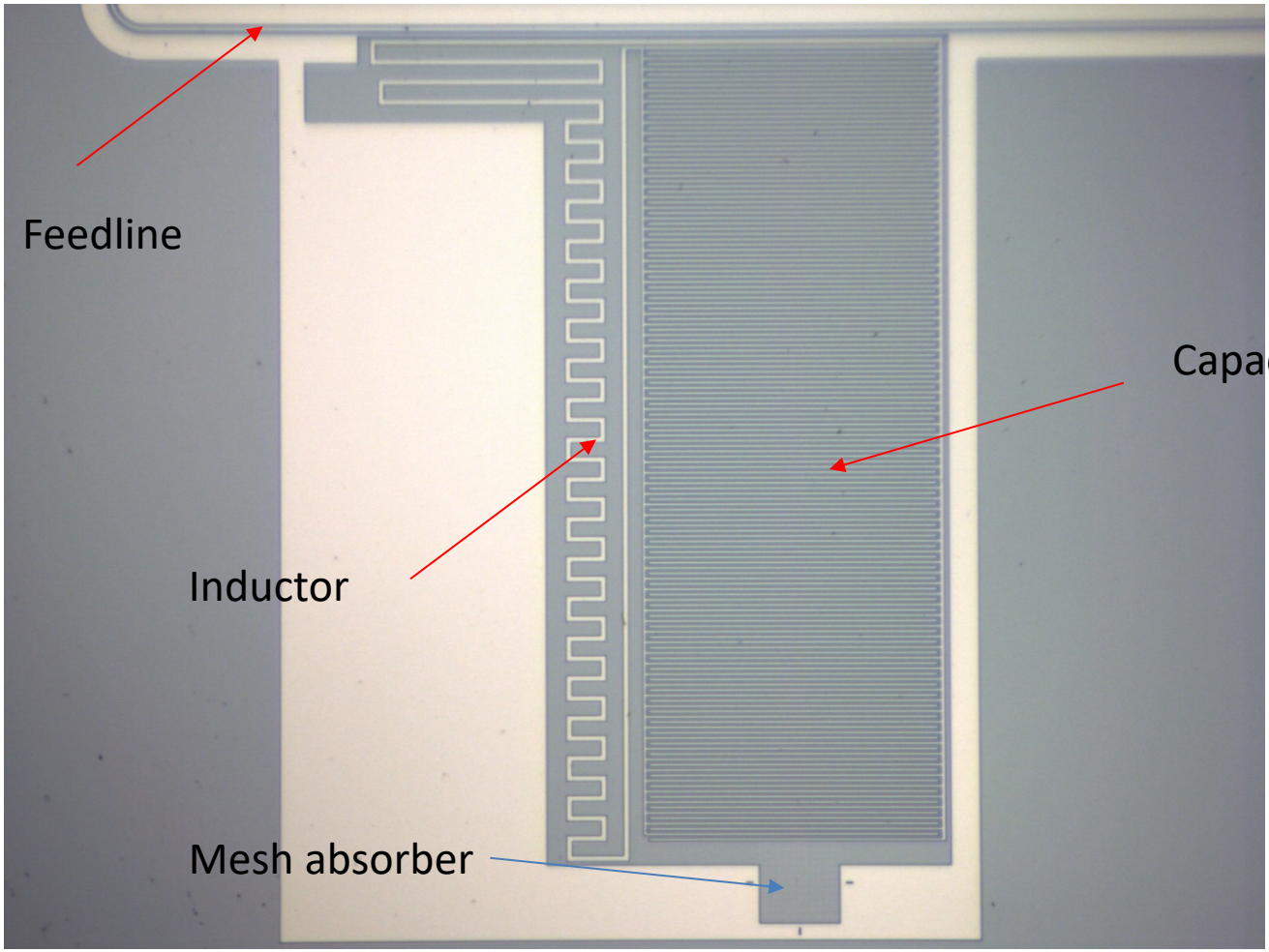
Total measured noise

$$NEP_{SN} = S_{SN}(f)/(\frac{dR}{dP})$$

Echternach, P.M., *et al.* Photon shot noise limited detection of terahertz radiation using a Quantum Capacitance detector. *Appl. Phys. Lett.* **103**, 053510 (2013).

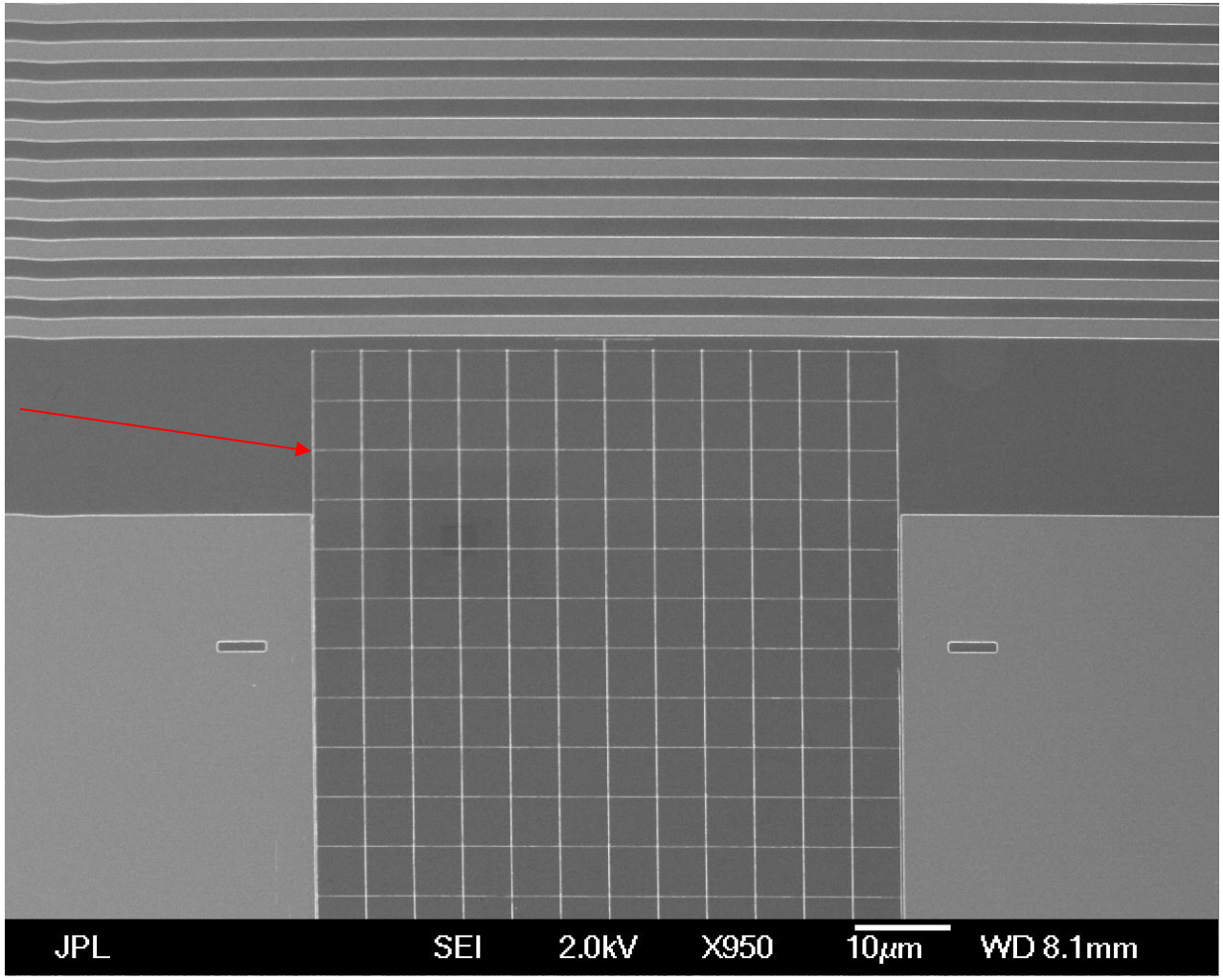
Lens coupled mesh absorber LEQCD

- Need mesh absorber instead of antenna to better couple to spectrometer modes
- Lumped element resonator saves space and has better characteristics than CPW half wave resonator

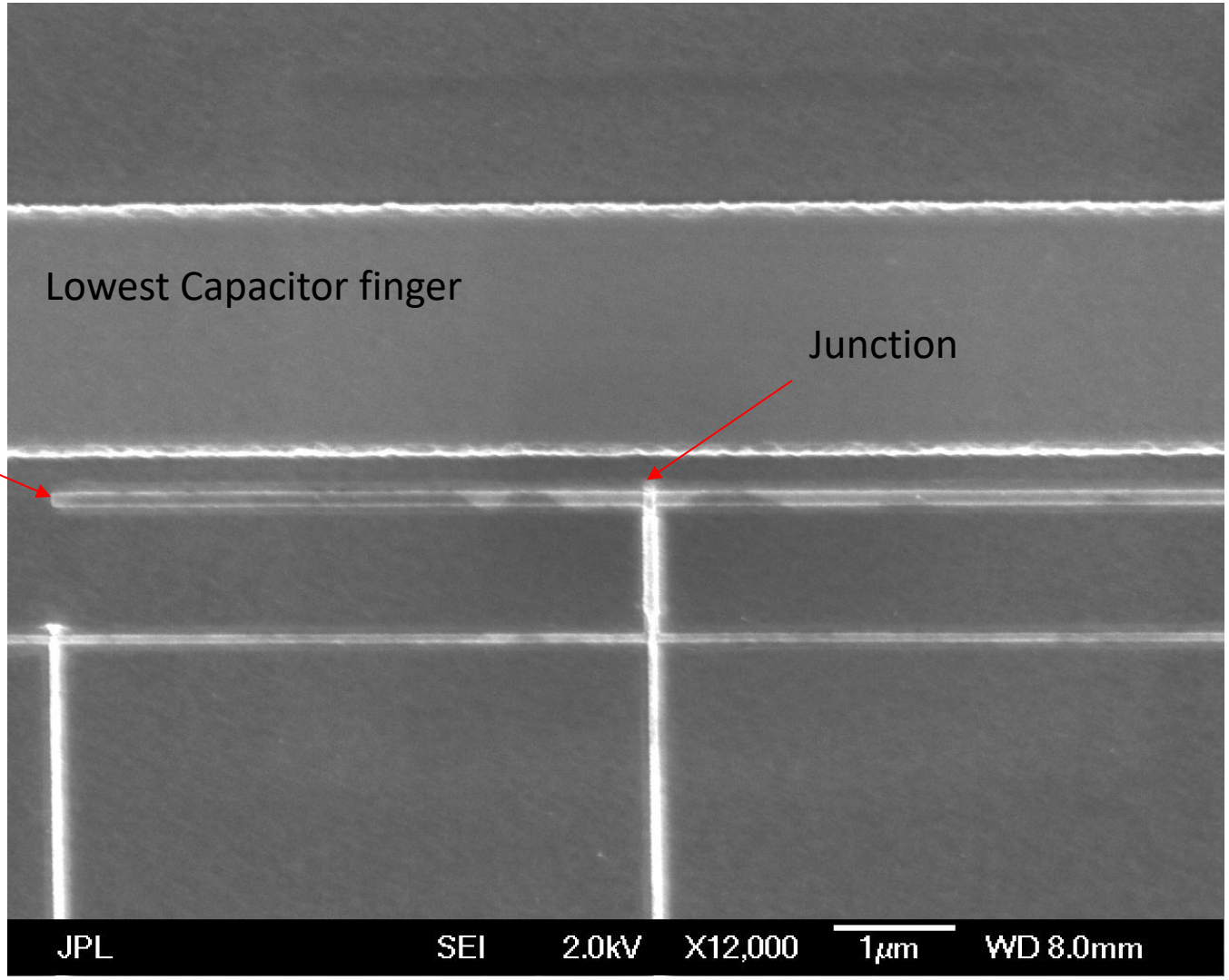


Lens coupled mesh absorber LEQCD

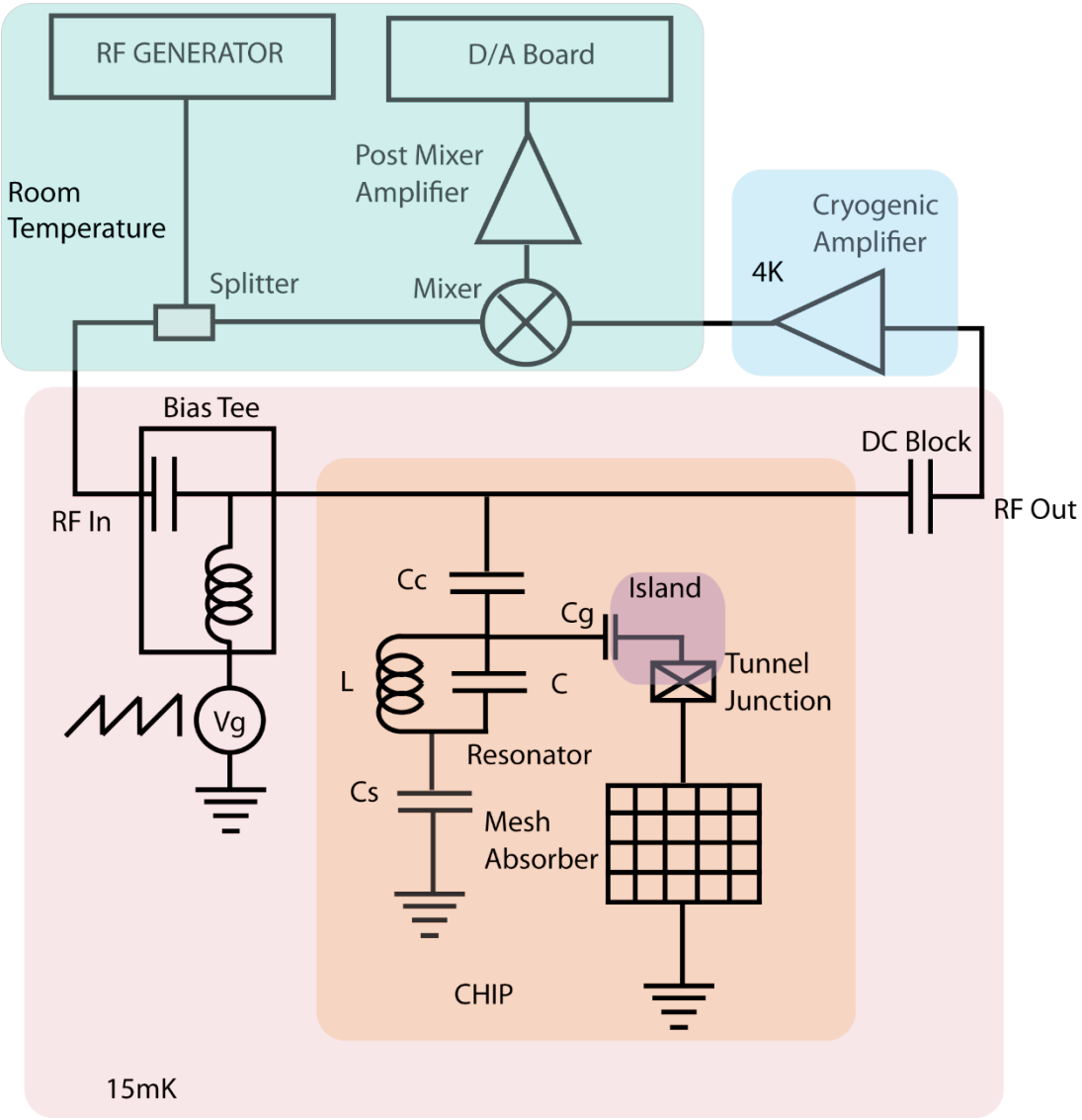
Mesh absorber



Lens coupled mesh absorber LEQCD



Measurement setup



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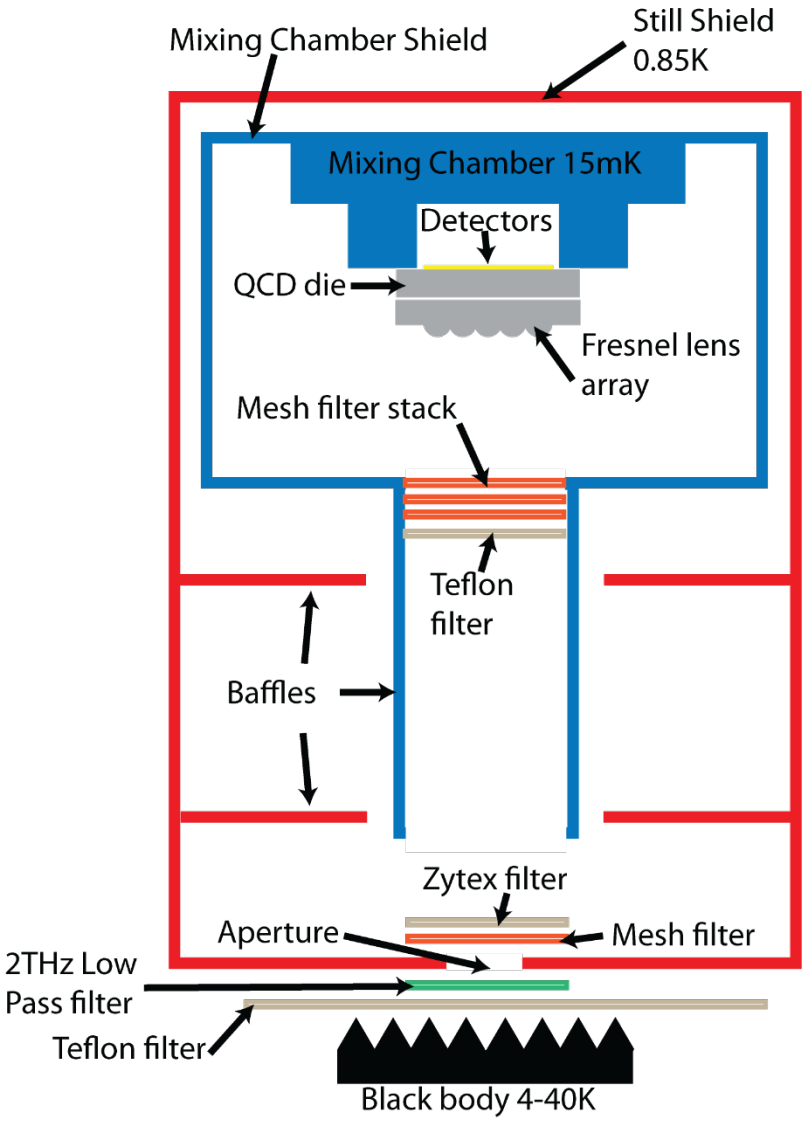
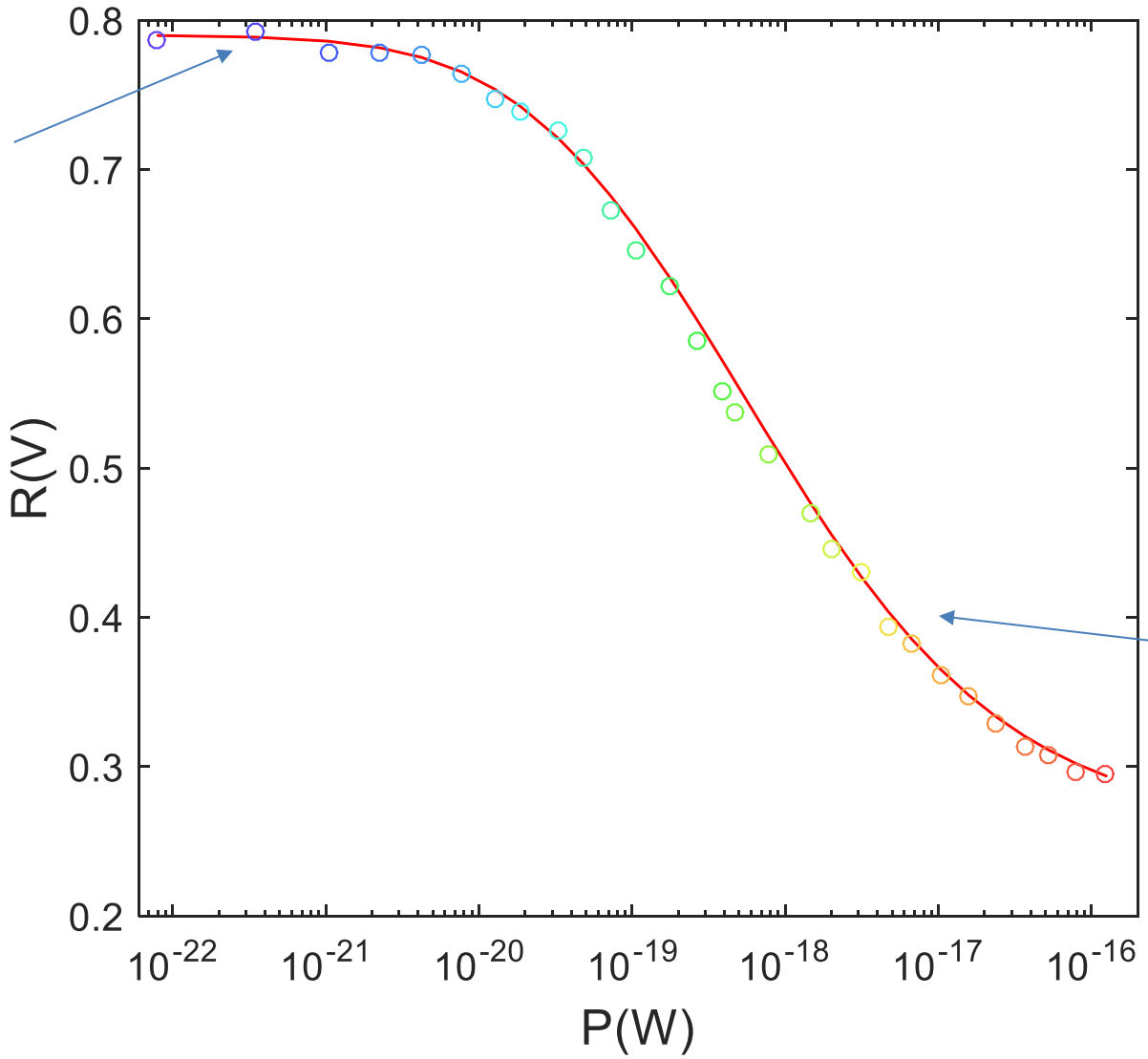


Lens coupled mesh absorber LEQCD

- QCD response as a function of optical power

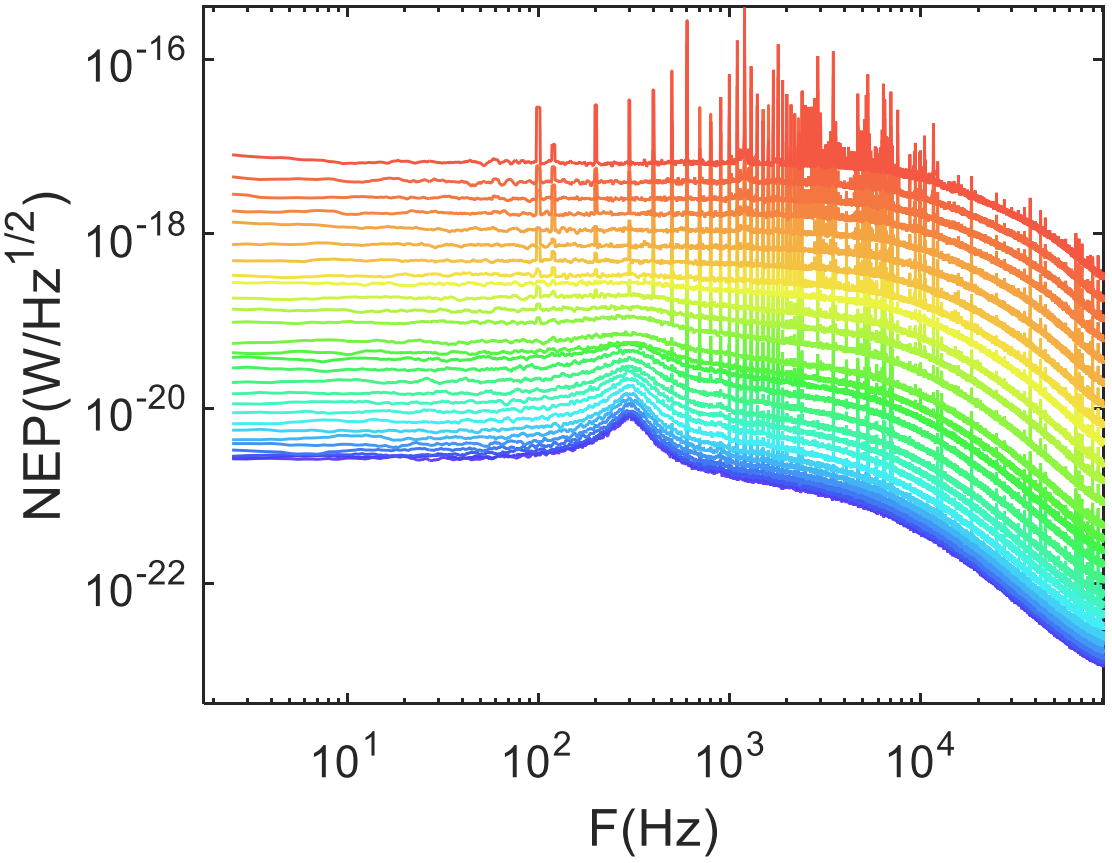


Tunneling in < base tunneling rate

Tunneling In >> Tunneling out -> Reaching saturation

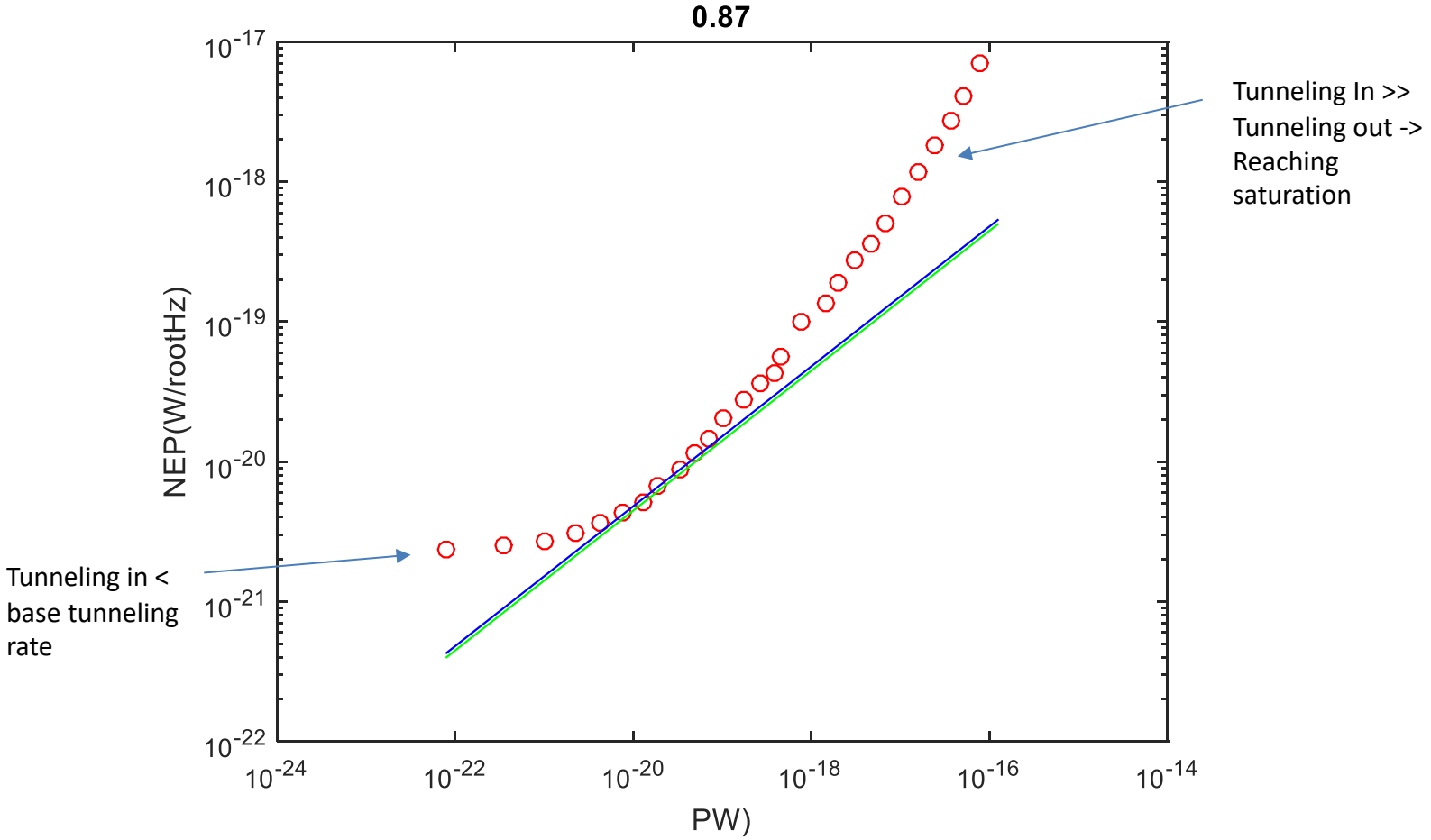
Lens coupled mesh absorber LEQCD

- NEP for various levels of optical illumination



- PSD time span 2s
- Gate sweep frequency 100Hz
- One sweep = 6 peaks
- QC peaks = 600Hz

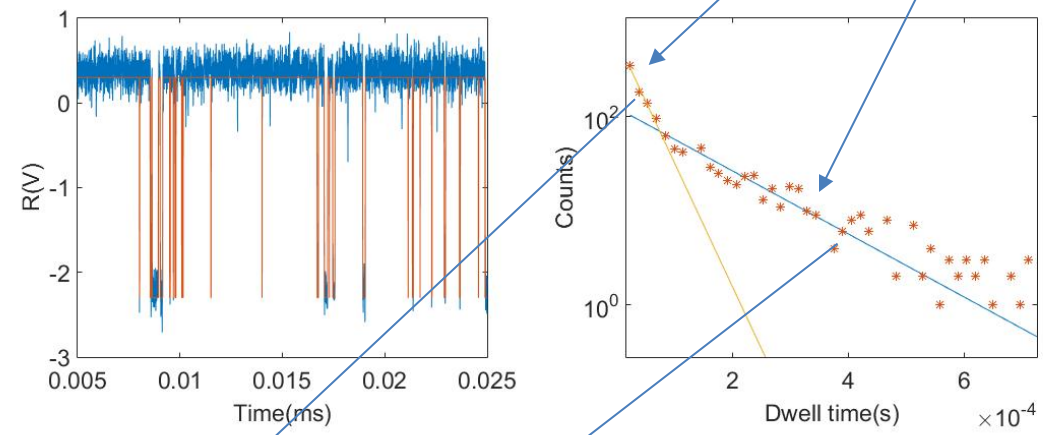
Lens coupled mesh absorber LEQCD

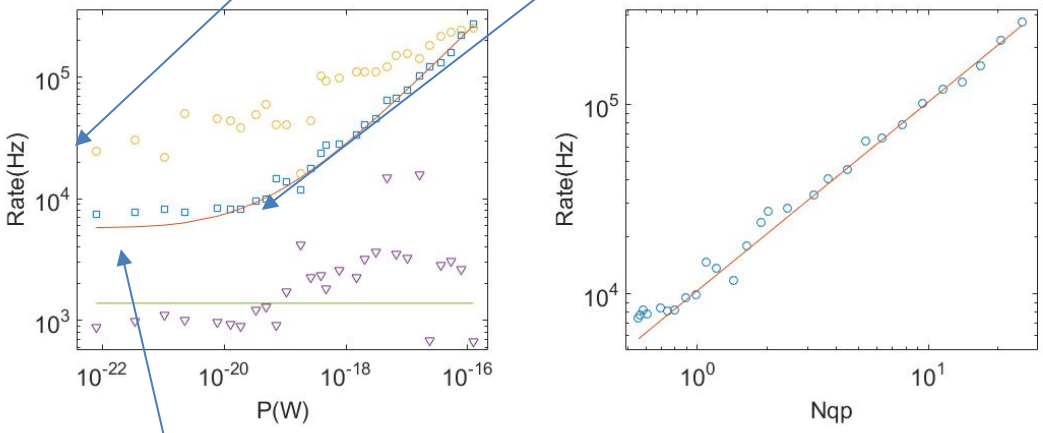


- $P^{1/2}$ dependence implies photon noise limited performance
- Efficiency extracted form ratio of measured NEP and photon shot noise NEP
- Should be able to detect single photons

Search for Single Photon Events – clues from DC biased time streams

$$\frac{dN_{qp}}{dt} = -RN_{qp}^2 - \frac{N_{qp}}{\tau}$$



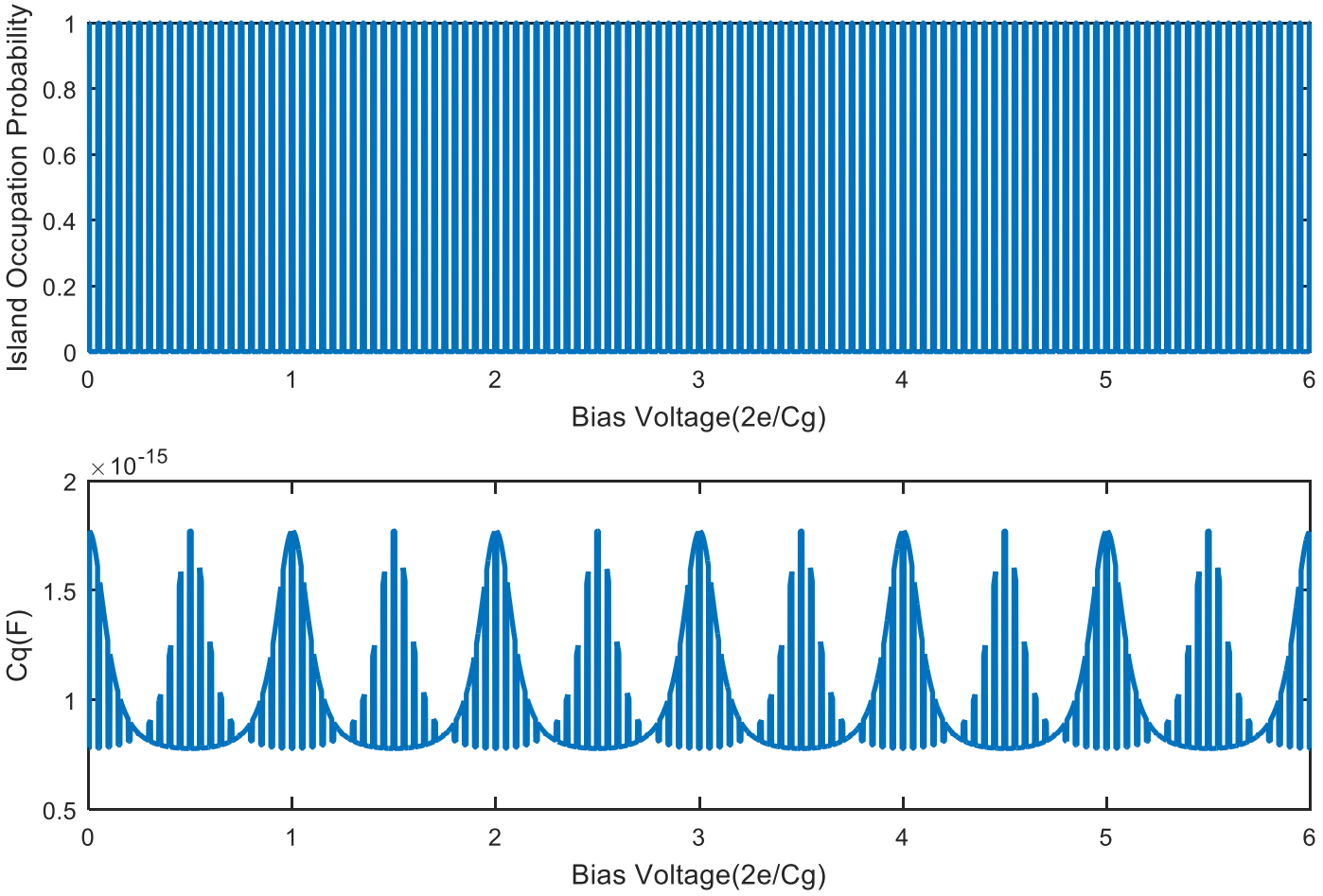


Background tunneling rate ~ 8kHz

- Measure time trace while DC biased
- Obtain histogram of dwell times
- Fit histogram to exponential decay
- Rate for longer times is due to residual lifetime
- Faster rate at shorter times due to single photons
- Tried to look for those faster events in smaller chunks of time stream – DAQ rate not fast enough to get good signal to noise ratio
- Can estimate how fast the initial tunneling rates are from the measured tunneling rates versus number of quasiparticles
- One photon generates on average 20 quasiparticles=> instantaneous rate about 220kHz

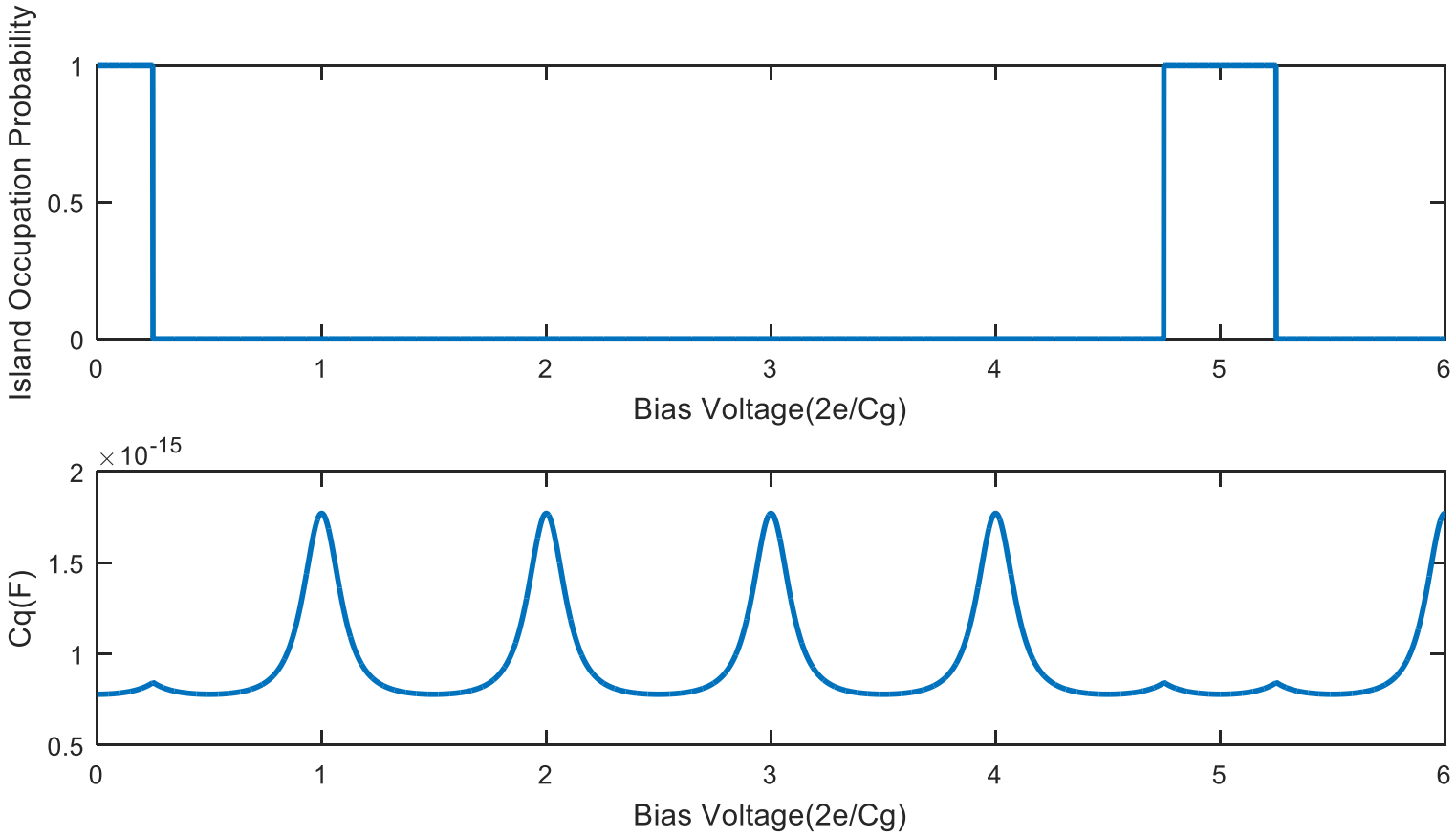
How to filter out background tunneling

Gate sweep frequency << Tunneling in rate



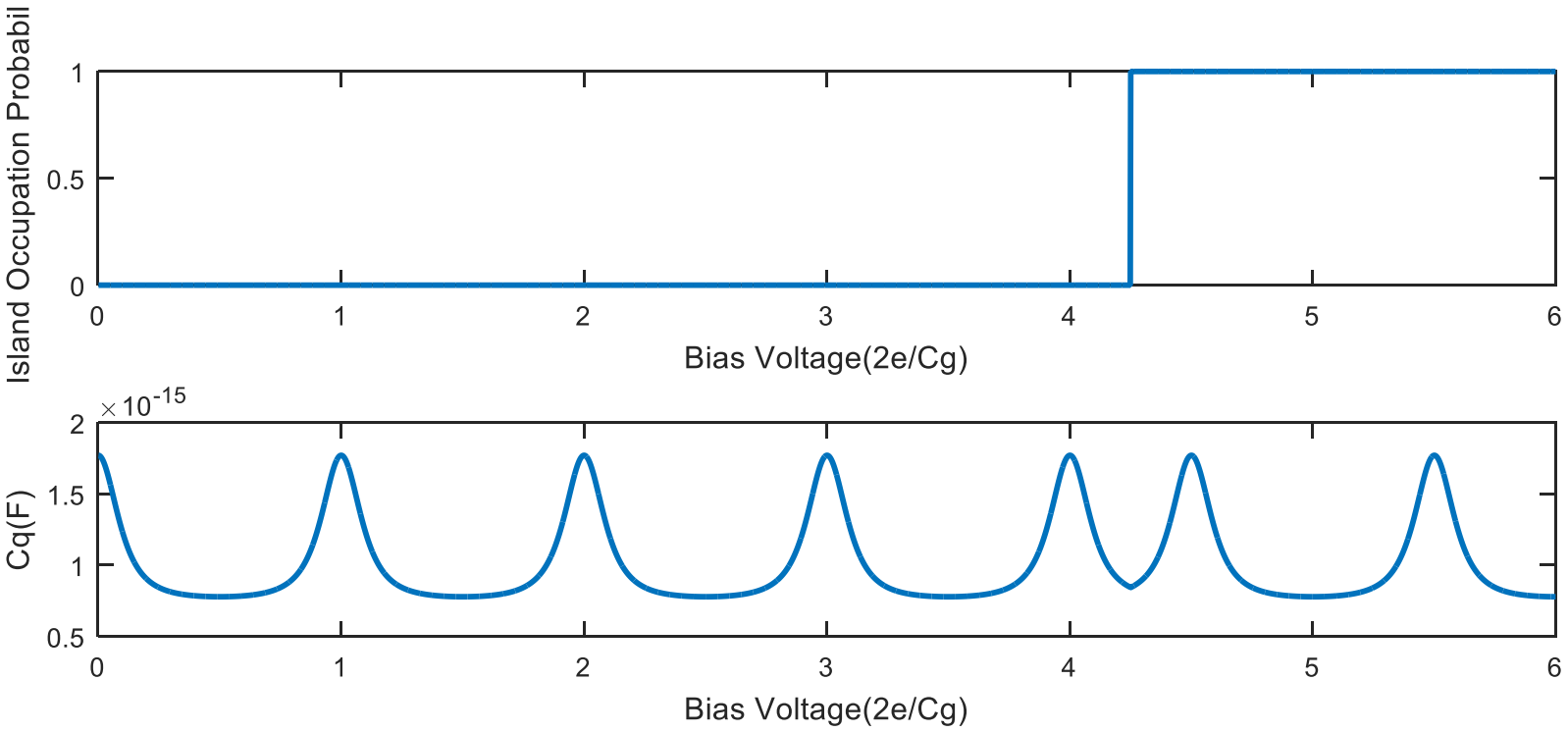
How to filter out background tunneling

Gate sweep frequency > Tunneling in rate – effect of photon absorption

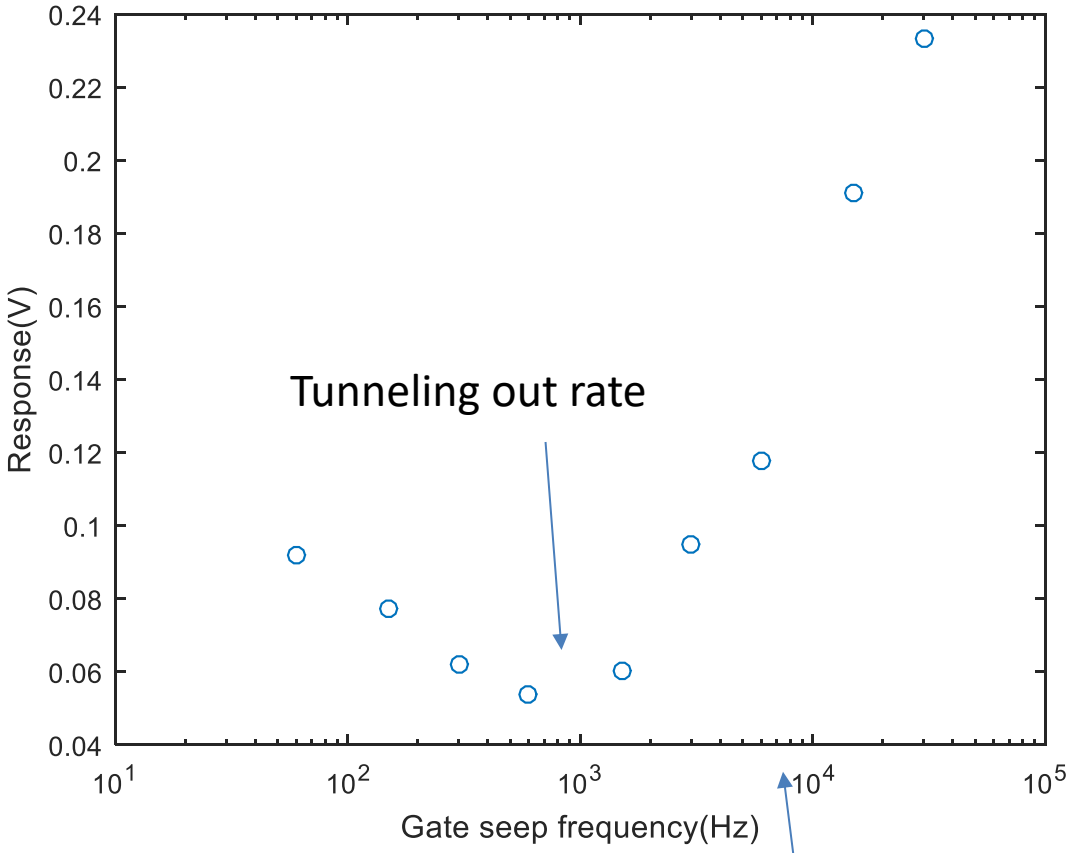


How to filter out background tunneling

Gate sweep frequency > Tunneling in rate – effect of background tunneling = e-shifts



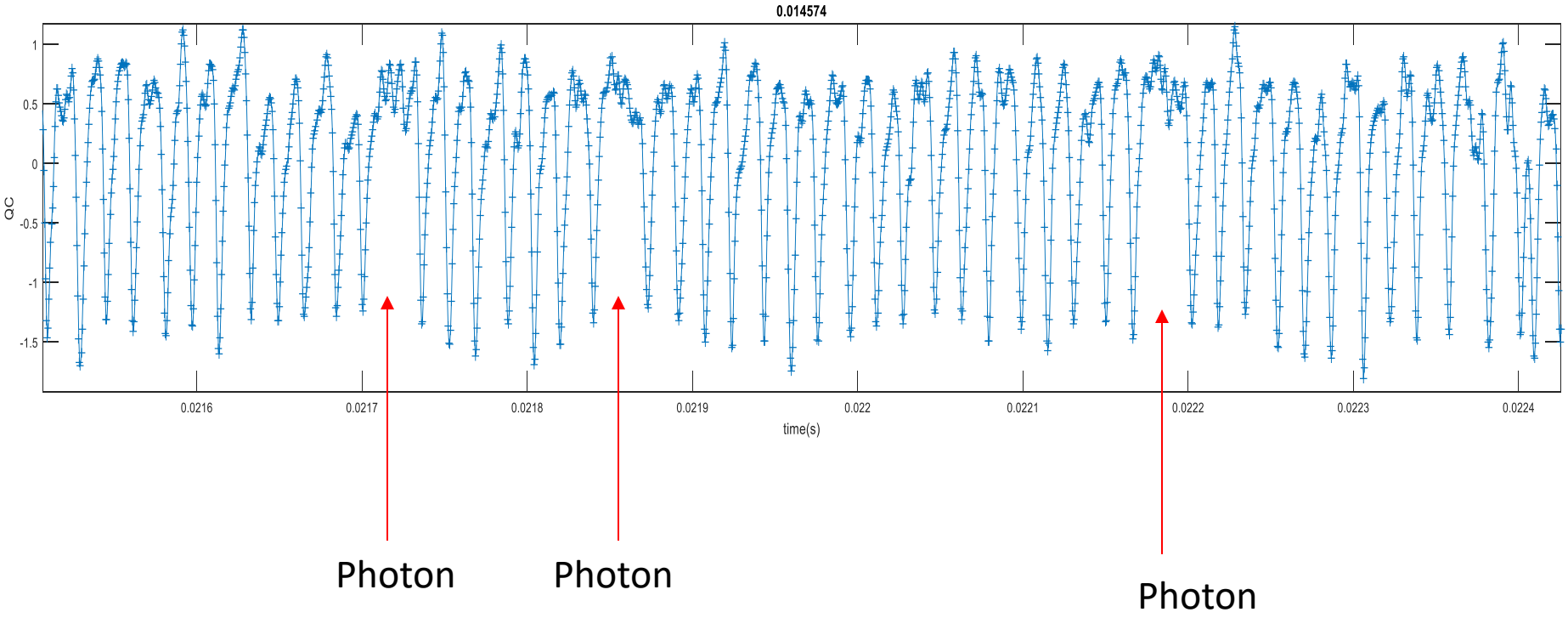
How to filter out background tunneling



Background tunneling in rate

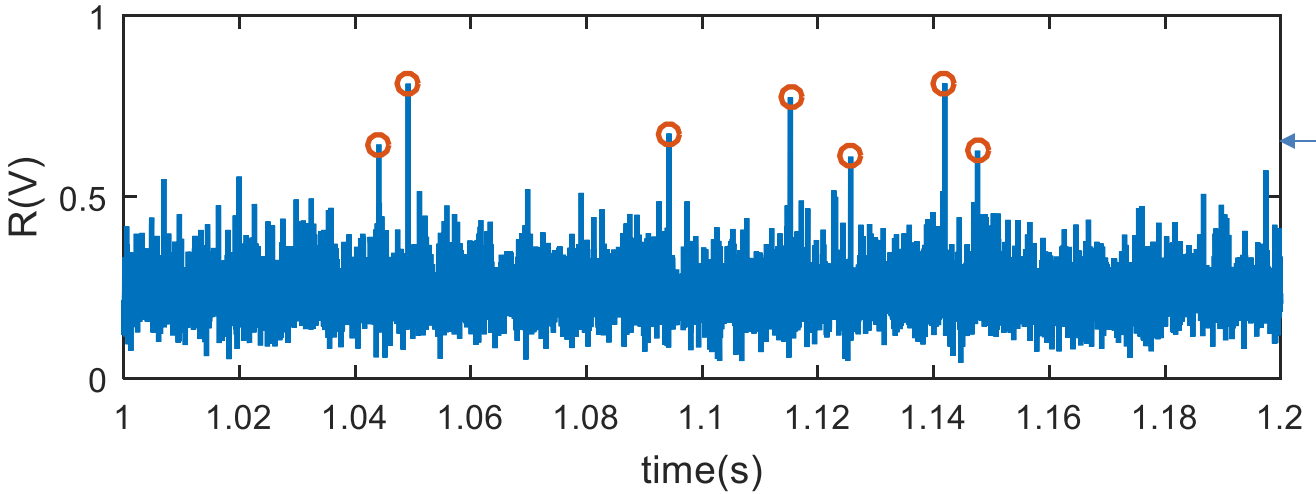
“ Fast sweep reveals single photon events spoiling QC signal

- Sweep rate ~ 22kHz spanning 3 Quantum Capacitance Peaks => effective sweep rate ~ 66kHz
- Should block background tunneling while still allowing tunneling due to single photon absorption
- Raw QC time trace should be absolutely periodic
- Gaps are due to high tunneling suppressing the Quantum Capacitance signal
- Therefore Gaps should be due to single photon absorption

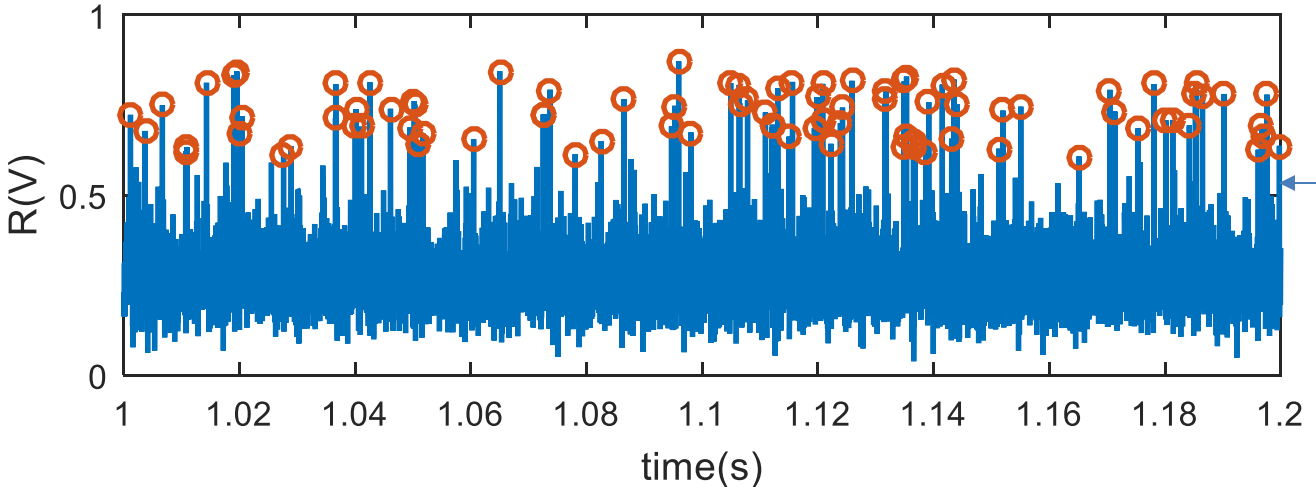


Variance evaluated in 30 us bins shows photon events

- From time traces calculated variance of slices corresponding to 2 QC peaks (to avoid problems at the edge of sweep with e-shifts) – slices are 30μs long
- Subtracted this trace from the maximum of the traces
- Gaps in the Quantum Capacitance trace will show up as peaks
- Repeat for different black body source temperatures



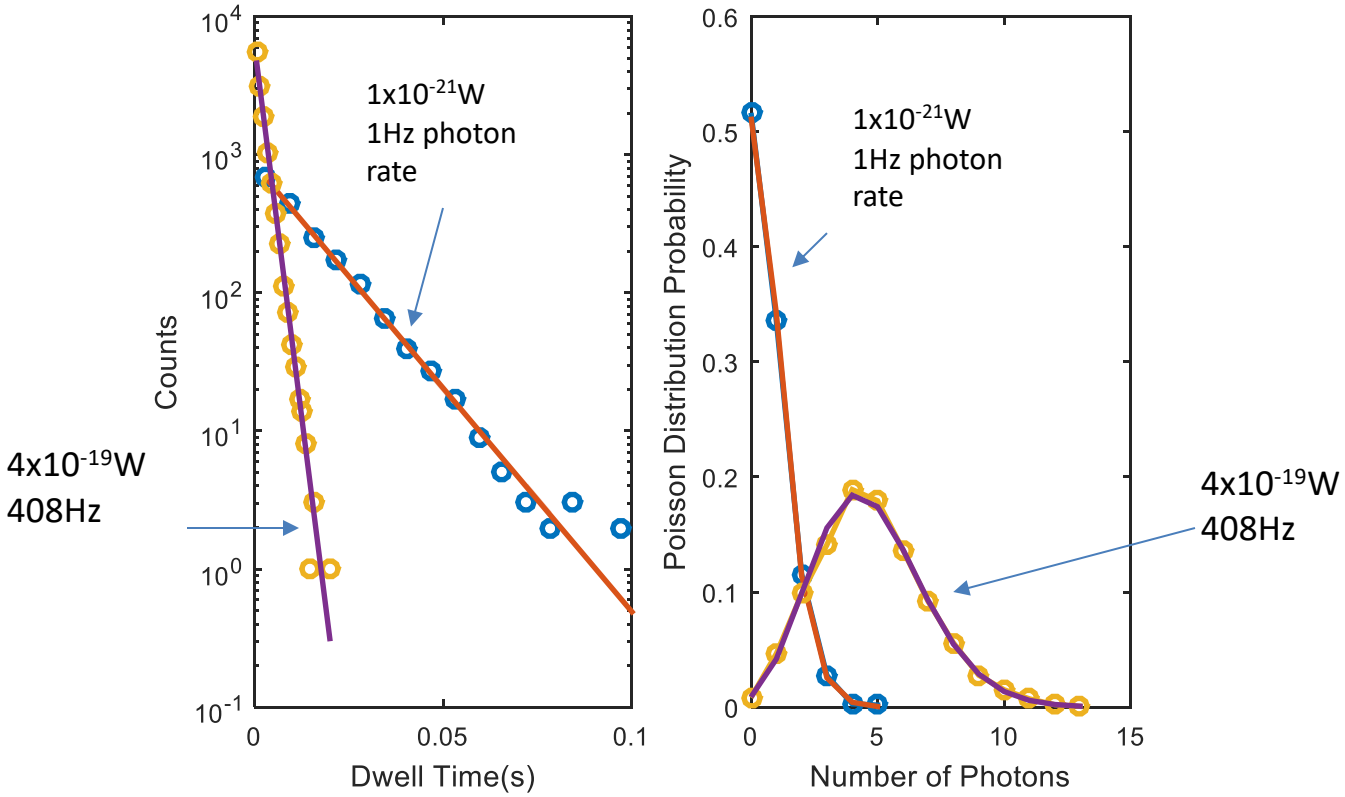
$1x10^{-21}$W
1Hz photon rate



$4x10^{-19}$W
408Hz

Photon arrival intervals follow Poisson statistics

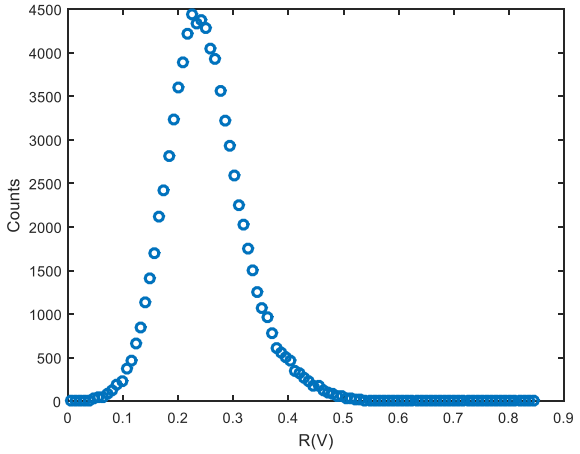
- From the photon time traces, extract dwell time histograms – exponential decay corresponds to Poisson statistics
- Calculate probability of having N photons within a time interval 36ms (Arbitrarily picked)
- Plot probability x number of photons; blue circles is measured, lines are calculated Poisson distribution probability (no fit, just using measured average number of photons)



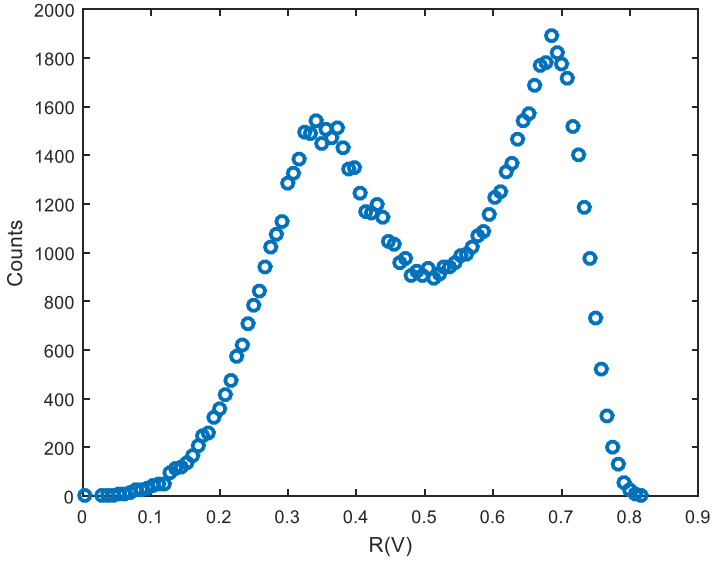
Photon arrival statistics

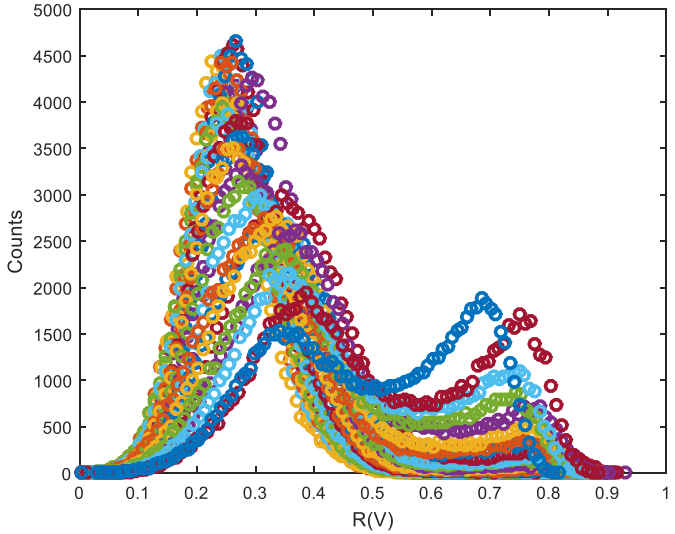
Histogram of response for various black body temperatures
For cold black body only peak around 0.25 exists
For hot black body peak around 0.6-0.7 is larger than peak at 0.25

Cold black body



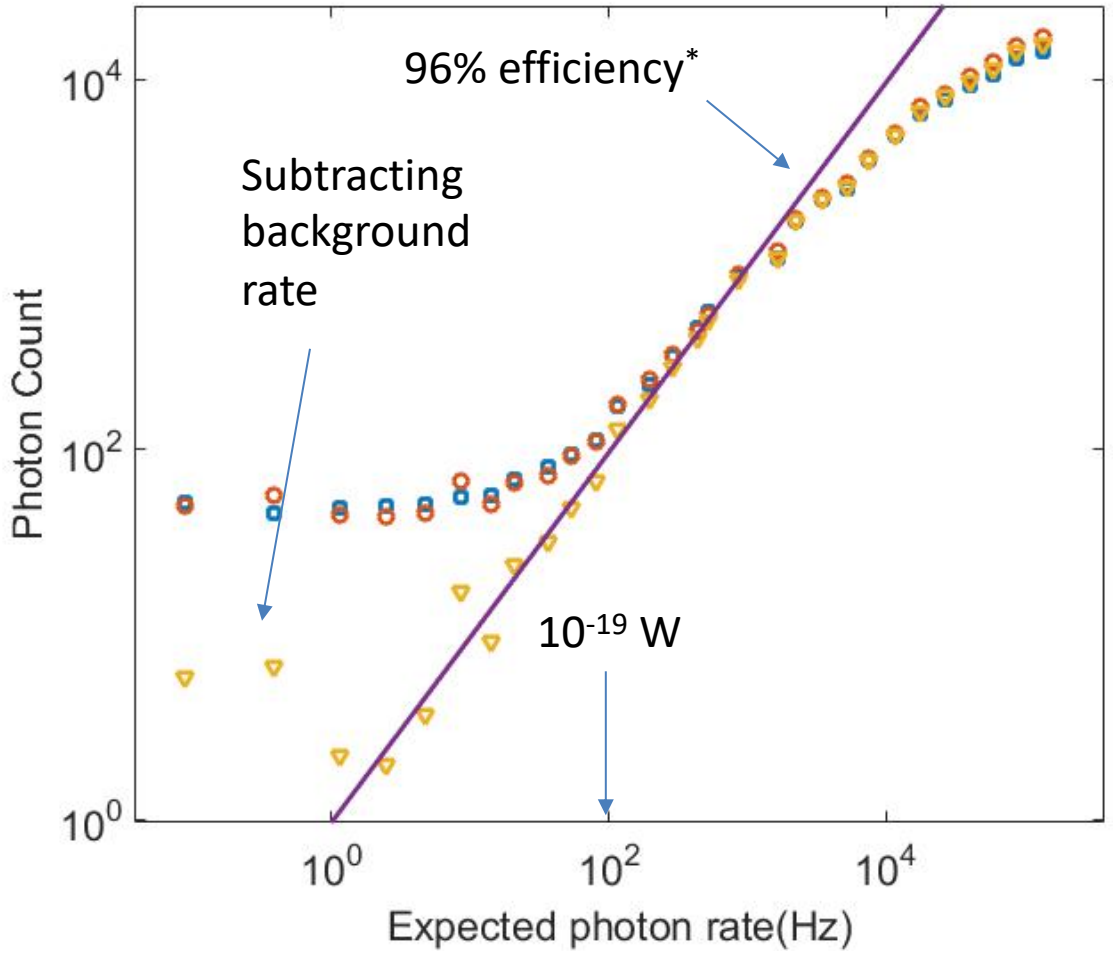
Hot black body





- Peaks get closer together at high black body temperatures due to filtering by the resonator of the high frequency stream
- Could lower resonator Q by stronger coupling at the expense of fewer channels

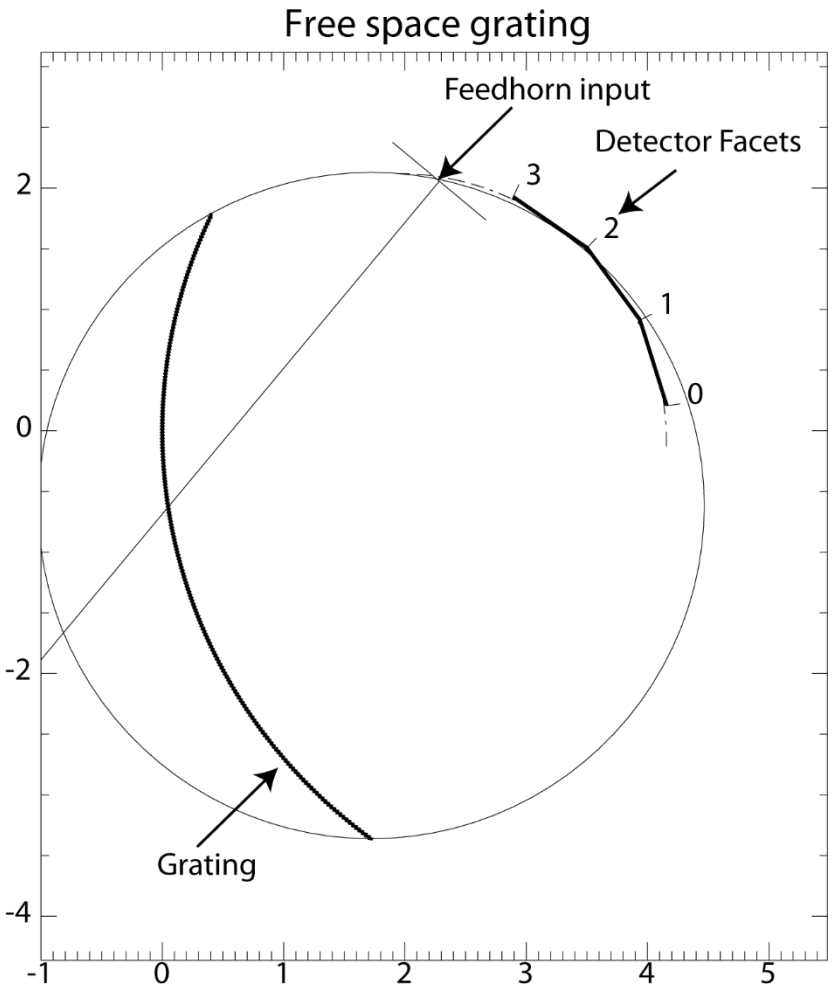
Counts of response between 0.6 and 0.9 versus number of expected photons



- Efficiency will decrease with when time intervals between photons become comparable to the time separation of two Quantum Capacitance Peaks

* With respect to absorbed power

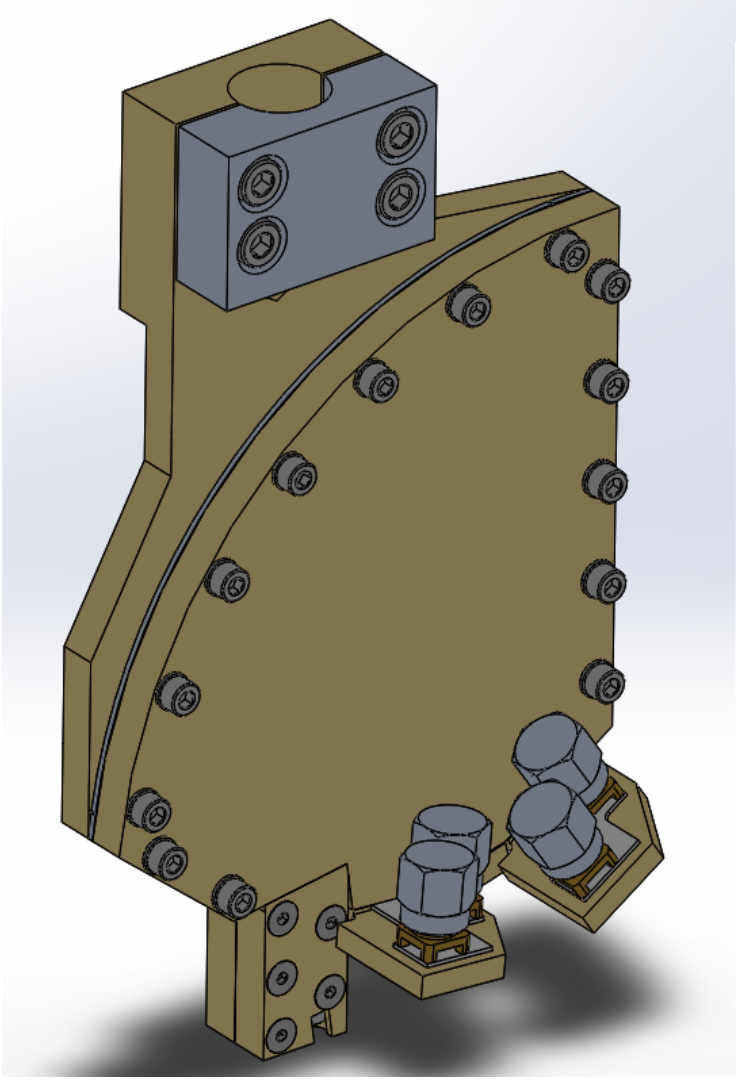
Free space spectrometer

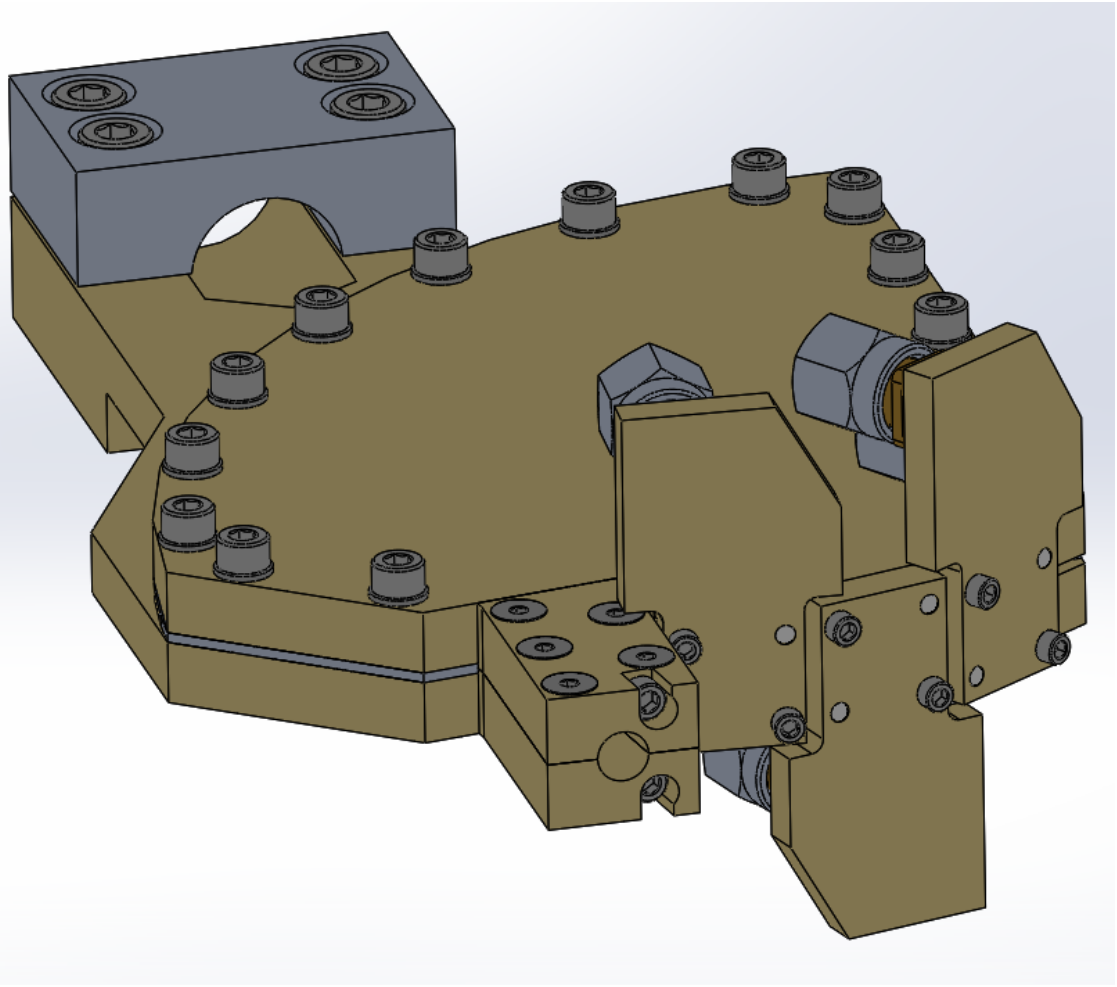


- Free space grating to avoid fragility of silicon input feed
- 860GHz to 1.8THz, 550-950GHz for silicon spectrometer
- R ~ 140 (600 measured on silicon spectrometer)
- 3 detector chips as opposed to 19. Easier assembly and better RF performance

Matt Bradford

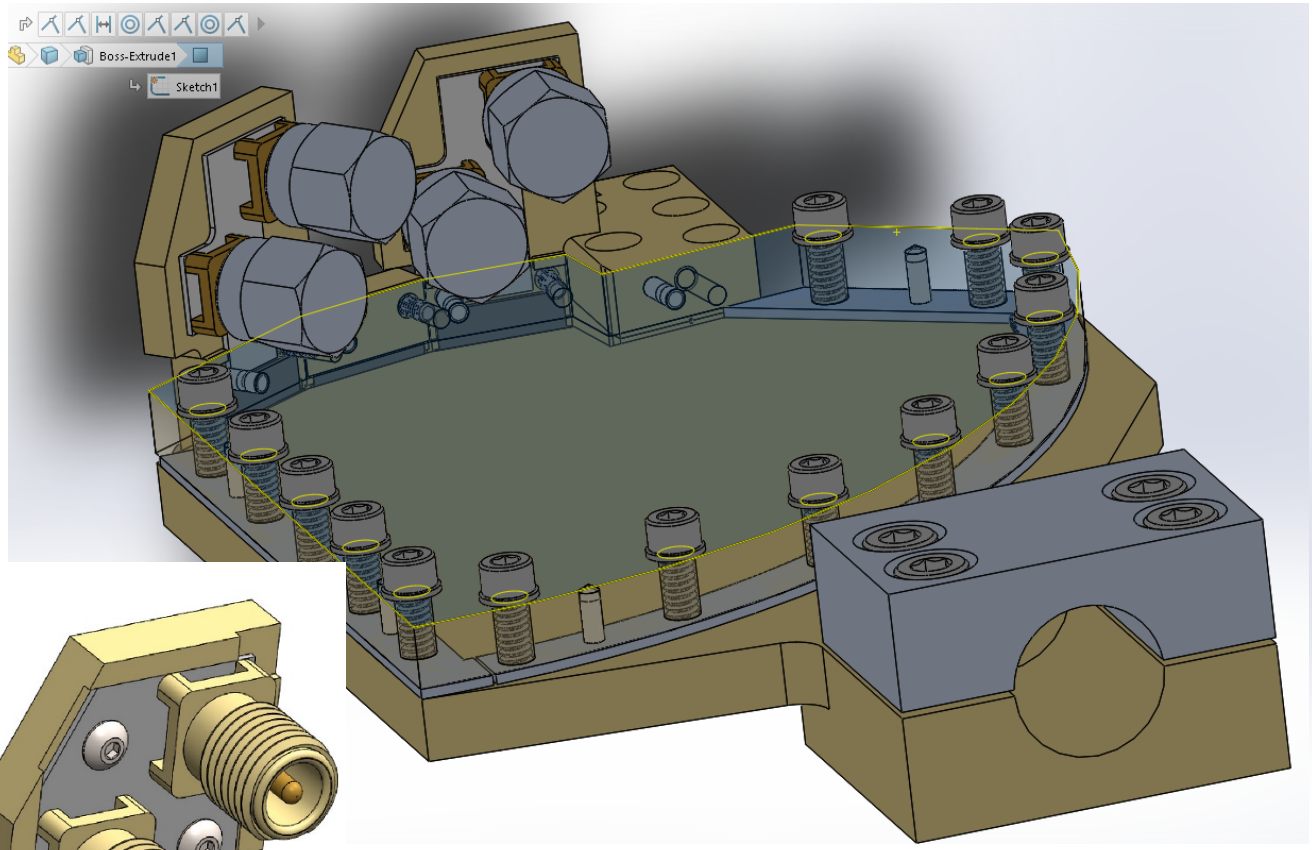
Grating spectrometer design

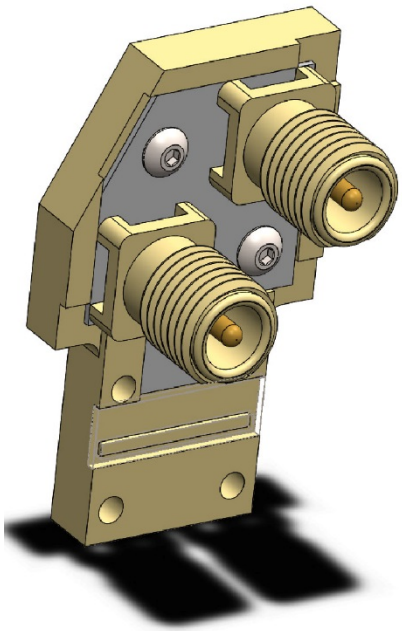


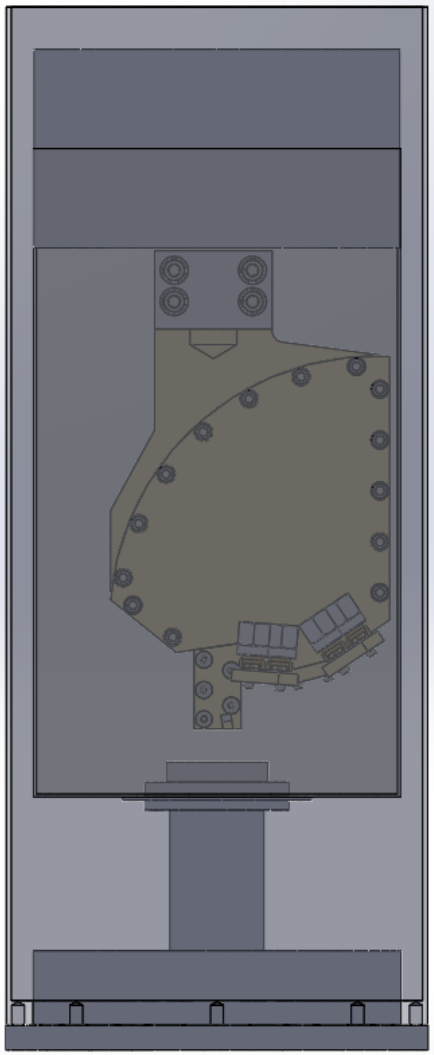


Theodore Reck, Darren Hayton, Matt Bradford and Maria Alonso

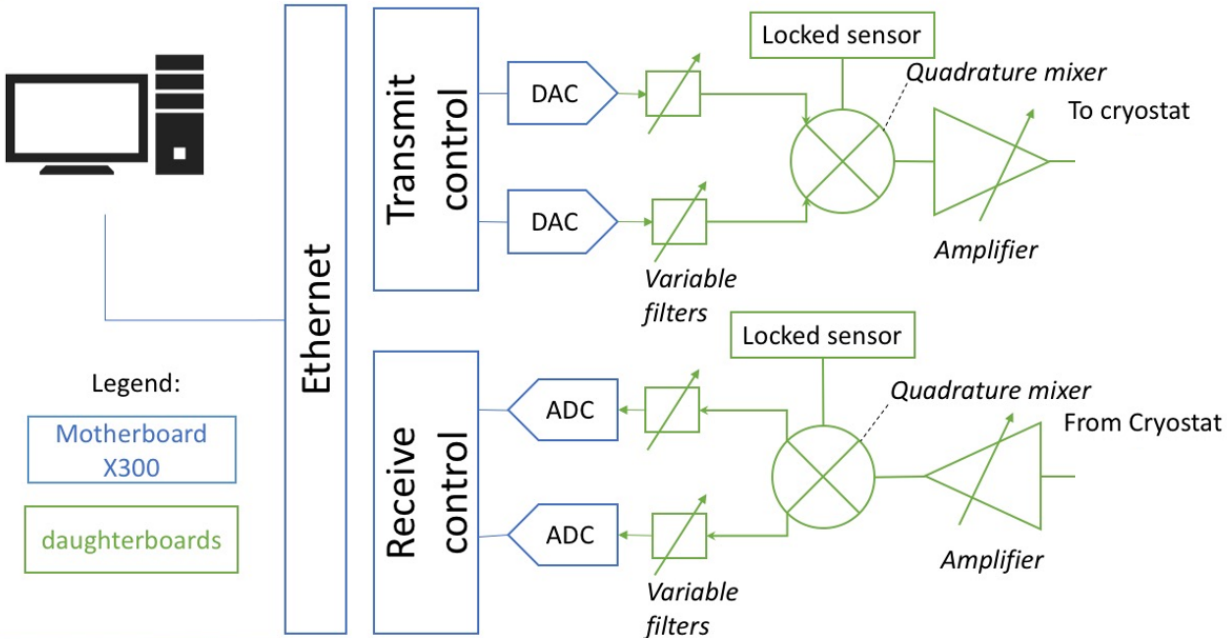
Grating spectrometer design







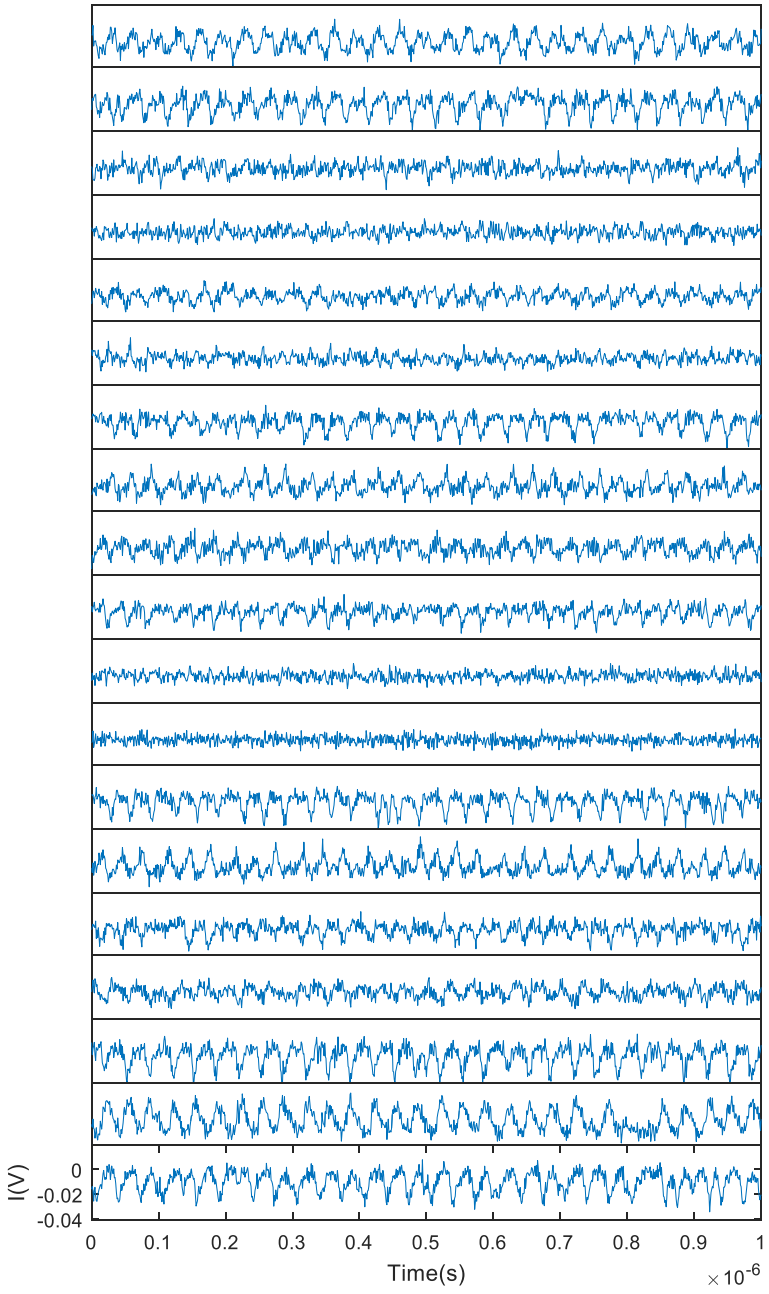
Multiplexed readout X300 USRP – Ettus research

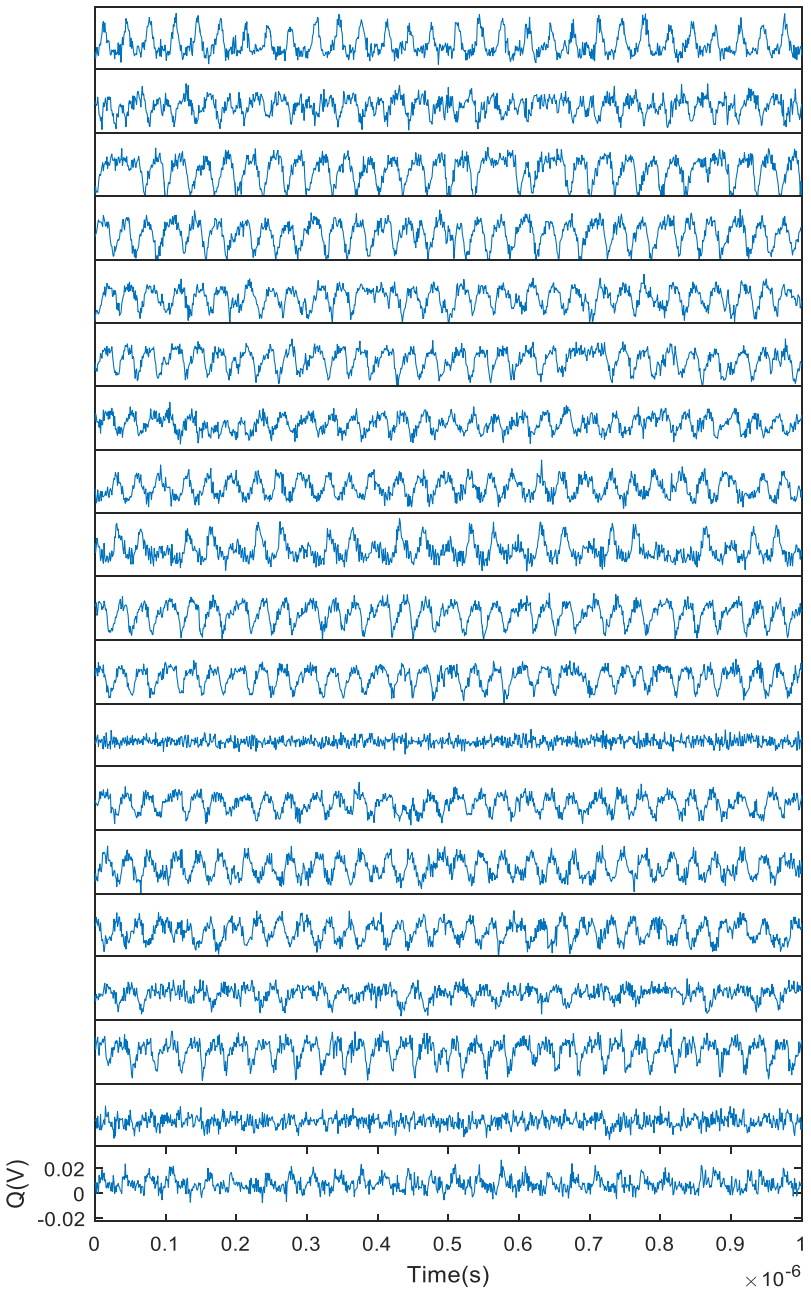


- Uses libraries that are called by python scripts
- 100 MHz bandwidth with current software
- 200 MHz bandwidth with next generation software
- Using two high speed daughterboards will increase bandwidth to 400MHz

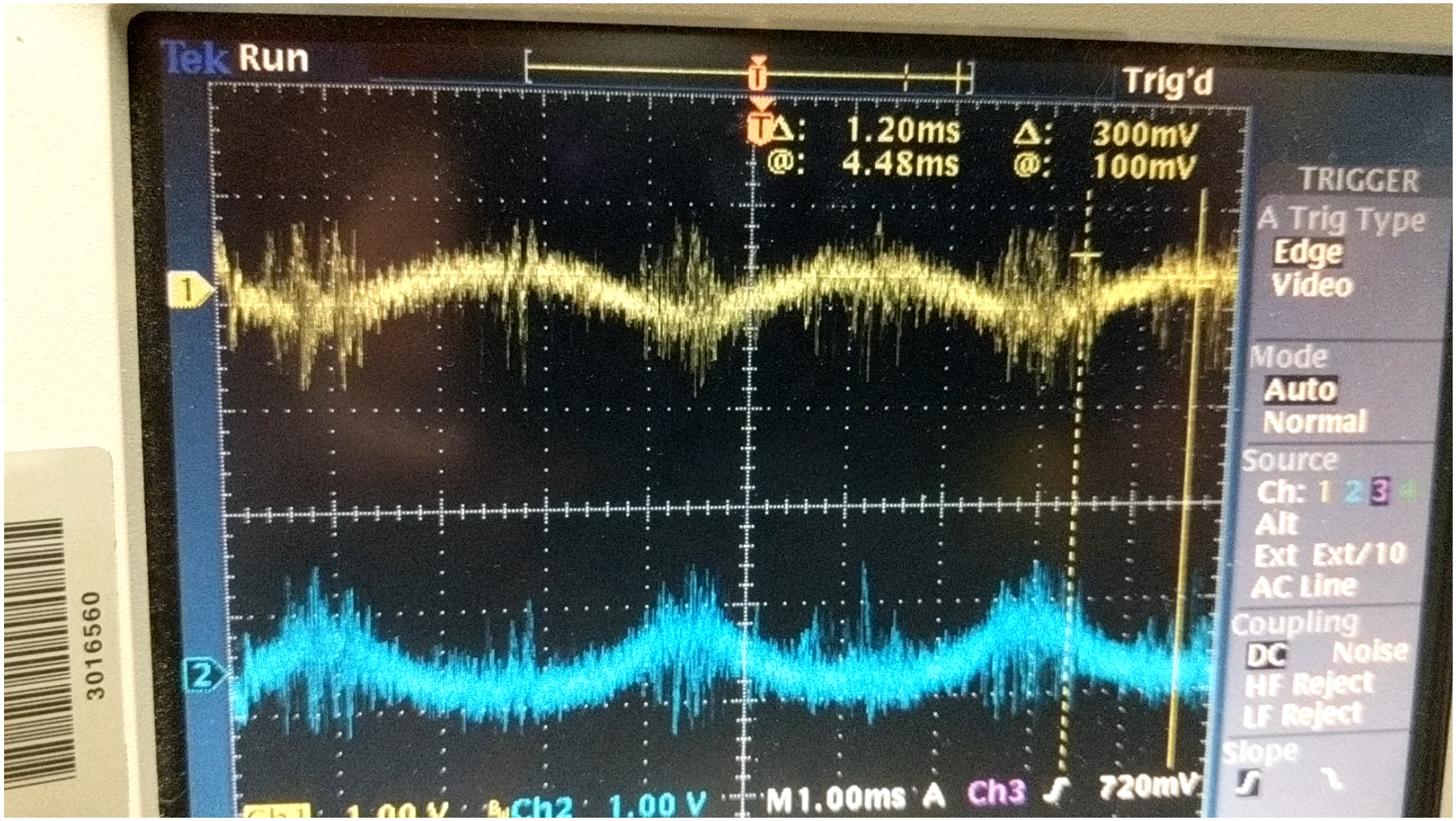
Readout system being developed by Lorenzo Minutolo and Roger O'Brient at JPL

19 channels readout simultaneously

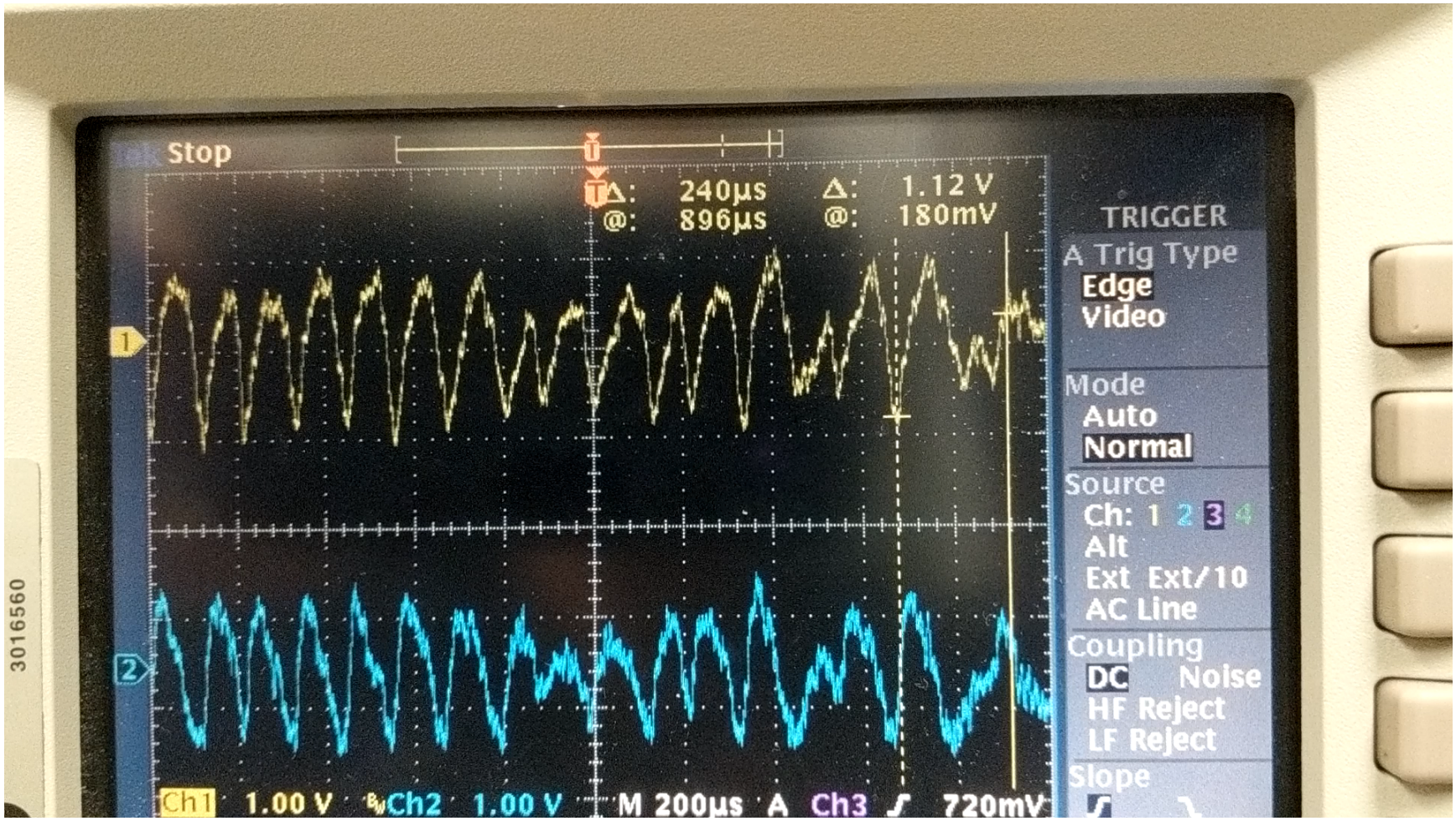




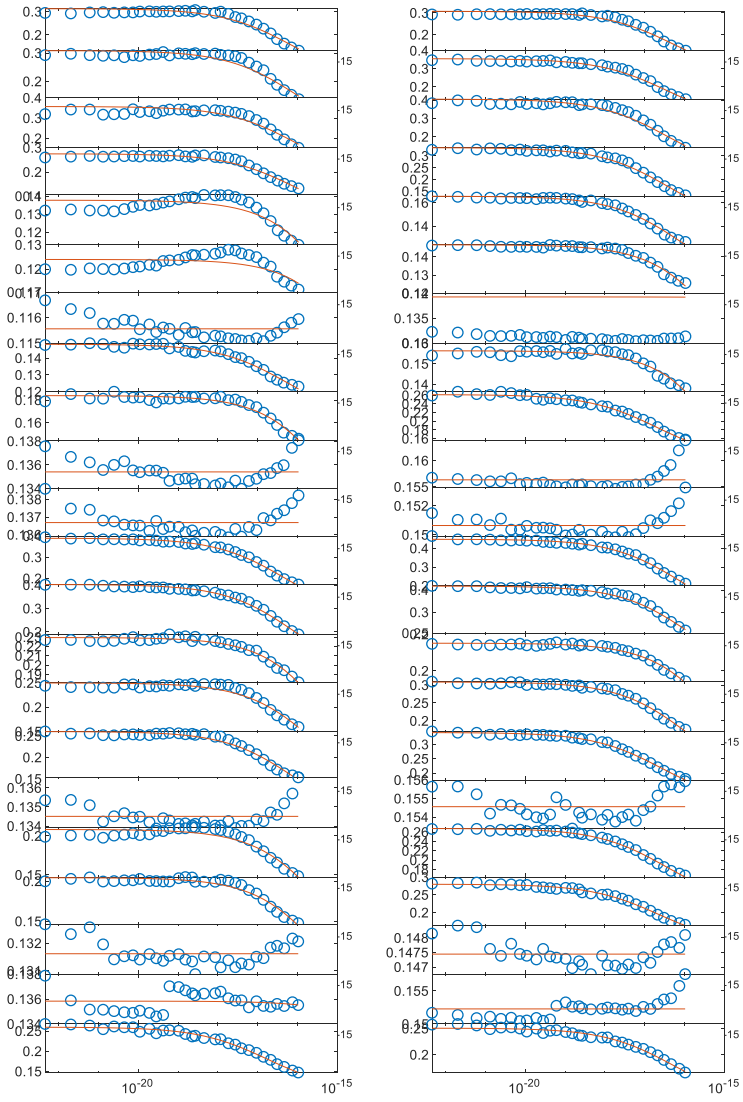
Real time measurements



Real time measurements

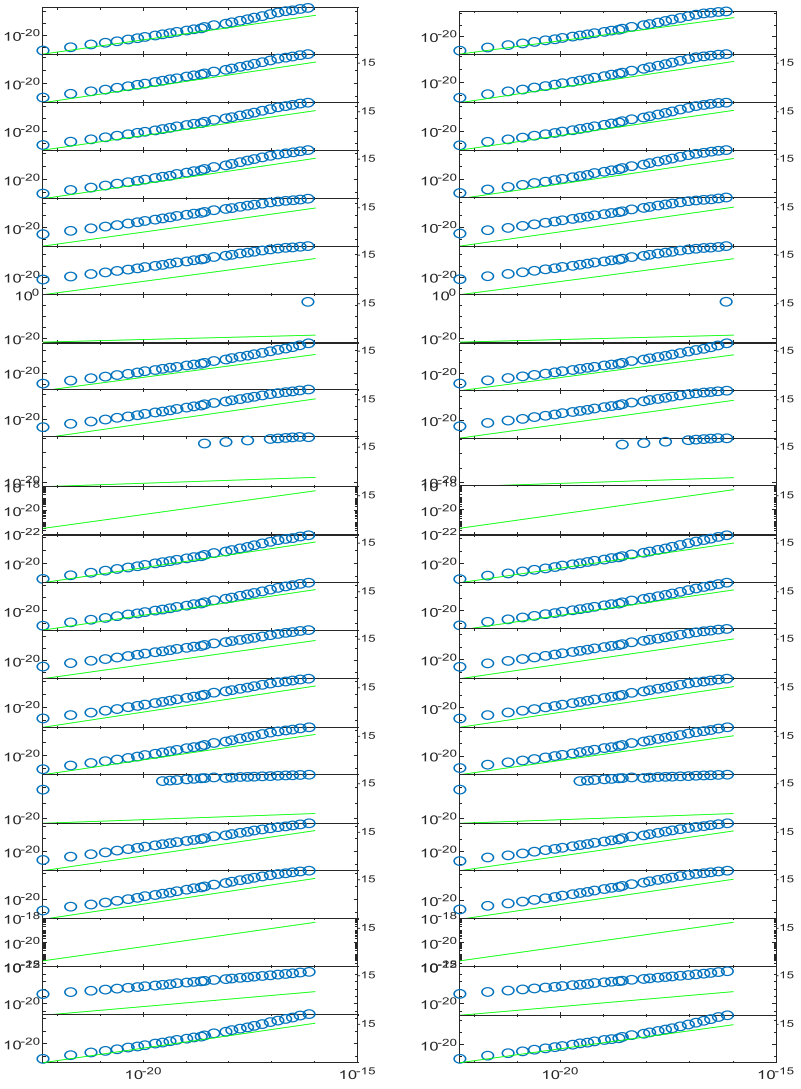


5x5 array of low frequency readout QCDs



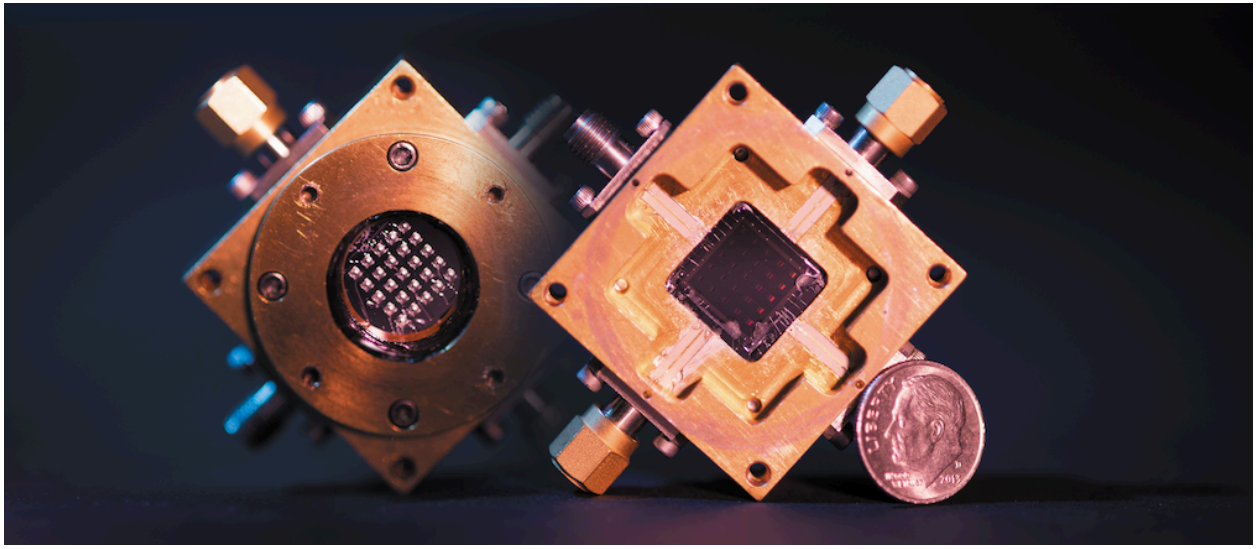
- 614 to 644 MHz
- Consume less power
- Higher Q resonators
- Samller frequency spacing

5x5 array of low frequency readout QCDs



Conclusion

- QCDs are the most sensitive far-IR detectors
- Meet NEP requirements of the Origins Space Telescope
- Photon counting in the far-Infrared demonstrated
- Small array with multiplexed readout demonstrated
- Working on Spectrometer demonstrations
- Lower readout Frequency demonstrated
- Working on large arrays of photon counters



Thank you for your attention!